Evidence Report:

Risk of Incompatible Vehicle/Habitat Design

Mihriban Whitmore, Ph.D.	NASA Johnson Space Center
Kerry McGuire, Ph.D.	NASA Johnson Space Center
Sarah Margerum, M.S.	Lockheed Martin, NASA Johnson Space Center
Shelby Thompson, Ph.D.	Lockheed Martin, NASA Johnson Space Center
Christopher Allen, M.S.	NASA Johnson Space Center
Charles Bowen, Ph.D.	Lockheed Martin, NASA Johnson Space Center
Bernard Adelstein, Ph.D.	NASA Ames Research Center
Susan Schuh, M.S.	MEI Technologies, NASA Johnson Space Center
Vicky Byrne, M.S.	Wyle, NASA Johnson Space Center
Doug Wong, P.E.	NASA Johnson Space Center

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National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

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Risk of Incompatible Vehicle/Habitat Design

The *Risk of Incompatible Vehicle/Habitat Design* is identified by the NASA Human Research Program (HRP) as a recognized risk to human health and performance in space. The HRP Program Requirements Document (PRD) defines these risks. This Evidence Report provides a summary of the evidence that has been used to identify and characterize this risk.

Executive Summary

To promote safe and efficient human performance during space missions, it is important to consider in the design process the effects of microgravity, acceleration, vibration, and other environmental conditions, as well as human capabilities and limitations with respect to the use of equipment, and how those may change on long-duration journeys. When these are not considered, there is a risk of incompatible vehicle/habitat design. This risk applies to all habitats in space. Examples of short-term effects due to this risk include overexertion, difficulty in reading a checklist due to spacecraft vibrations or inadequate lighting, high temperature in a module due to inefficient co-location of habitability related hardware and excessive activities, difficulty donning a suit due to inadequate habitable volume, and difficulties communicating with fellow crewmembers due to high levels of noise in the cabin. Performance-related inefficiencies may include unnecessary translations between workstations to complete tasks, increased task completion time due to difficulty in accessing equipment, and lack of restraints for performing tasks requiring stability. Examples of long-term effects include ergonomic-related cumulative trauma disorders due to repetitive motions and/or sustained maintenance of awkward postures, insufficient workspace clearances resulting in frequent over-exertions, suit hardware requiring sustained performance at maximal levels, and permanent hearing loss. Interacting with a vehicle/habitat environment that does not accommodate the crew along all anthropometric ranges, and does not consider human capabilities, limitations, and how these may change during long-duration spaceflight, could lead to injuries, crew frustration, and/or mission failure.

In order to develop a work environment design that can accommodate crew capabilities and limitations, these physical capabilities and limitations must be well understood and documented for all of the mission stages. Vehicle/habitat designers will have to understand the strengths and weaknesses associated with performing tasks in microgravity and reduced gravity environments, and the minimum net habitable volume required to accomplish these tasks to prevent and reduce injuries and inefficiencies. Mockups and simulators with an appropriate level of fidelity to accurately represent the vehicle/habitat layout configuration will be key to properly replicating the vehicle/habitat configurations experienced in microgravity and reduced gravity environments.

Key contributing factors to the risk of incompatible vehicle/habitat design include: 1) Anthropometric and biomechanical limitations, 2) Motor skill/coordination or timing, 3) Space and lunar visual environments, 4) Vibration and g-forces, 5) Noise interference, 6) Seating, restraints and personal equipment, 7) Visibility/window design & placement, and 8) Vehicle/habitat volume/layout.

Risk Statement

Given that vehicle, habitat, and workspace designs must accommodate variations in human physical characteristics and capabilities, and given that the duration of crew habitation in these space-based environments will be far greater than missions of the past, there is a risk of acute and chronic ergonomic-related disorders, resulting in flight and ground crew errors and inefficiencies, failed mission and program objectives, and an increase in crew injuries.

Risk Overview

During the design process, designers will use the following documents, which describe current habitat design standards, principles and processes, to reduce the risk of incompatible vehicle/habitat design:

1) NASA-STD-3001 Volume 2: This volume defines standards for spacecraft, internal environments, hardware, and software which the crew interfaces with during operations (NASA, 2011b).
2) NASA Procedural Requirements (NPR) 8705.2B: This document specifies the human-rating processes, procedures, and requirements (NASA, 2008).
3) NASA/SP-2010-3407 Human Integration Design Handbook (HIDH): A resource document to NASA-STD-3001 Volume 2, and provides technical information on many aspects of space system design for crew health, habitability, environment, and human factors (NASA, 2011a).
4) JSC 63557: Defines the verification method for Net Habitable Volume (NHV) requirements. This document defines NHV, provides the technique for calculating NHV, describes the process for monitoring and evaluating NHV and lists the expectations for development and delivery of NHV verification data (NASA, 2009b).

To promote safe and efficient human performance during space missions, it is important to consider in the design process, not only the effects of microgravity, acceleration, vibration, and other environmental conditions, but also human capabilities and limitations with respect to the use of equipment, and how those may change on long-duration journeys. When these are not considered, there is a risk of incompatible vehicle/habitat design. This risk applies to habitats that may include the launch and transfer vehicles, a pressurized suit or other occupied and confined space (e.g., space station, non-Earth outpost, re-entry capsule, rovers) designed for travel or operation outside Earth's atmosphere. Examples of short-term effects due to this risk include overexertion, difficulty in reading a checklist due to spacecraft vibrations or inadequate lighting, high temperatures in a module due to inefficient co-location of habitability related hardware and excessive activities, difficulty donning a suit due to inadequate habitable volume, and difficulties communicating with fellow crewmembers due to high levels of noise in the cabin. Performance-related inefficiencies may include unnecessary translations between workstations to complete tasks, and increased task completion time due to difficulty in accessing equipment or lack of restraints for performing tasks requiring stability. Examples of long-term effects include ergonomic-related/ cumulative trauma disorders that are a result of repetitive motions, sustained maintenance of awkward postures, insufficient workspace clearances resulting in frequent over-exertions, suit hardware requiring sustained performance at maximal levels, and permanent hearing loss. Interacting with a vehicle/habitat environment that does not accommodate the crew along all anthropometric ranges, and does not consider human capabilities and limitations, and how these may change during long-duration spaceflight could lead to injuries, crew frustration, and/or mission failure.

Although the adverse outcomes of this risk are more likely during the operational phase, the primary risk mitigation steps need to be initiated by identifying and implementing appropriate requirements and standards during the design, development, test, and evaluation (DDT&E) phases or pre-operational phases of a Program or Project. For example, development of a concept of operations early in the design phase is important in mitigating this risk since identifying specific mission activities and locations will help assure adequate clearances to minimize the need for awkward postures, reduce the need for overexertion, and establish the rationale for a reasonable net habitable volume. Similarly, defining critical aspects of the physical environment during the design phase helps drive relevant ergonomic requirements and ensures that the spacecraft or habitat environment is compatible with crew physical needs and limitations.

Examples of appropriate mitigations during the pre-design and design phases would be: establishing appropriate requirements for noise, lighting, and vibration levels; providing adequate net habitable volume in the design; simplifying tasks; reducing repetitive motions; and minimizing the duration of static loading or awkward postures. During the development, test, and evaluation phases, it will be critical to perform activities such as population analysis, digital modeling, simulations, and human-in-the-loop (HITL) evaluations in order to assess and prevent incompatibilities between the human and the vehicle/habitat.

In order to achieve a work environment design that can accommodate crew capabilities and limitations, these physical capabilities and limitations must be well understood and documented for all of the mission stages. Vehicle/habitat designers will have to better understand the strengths and weaknesses associated with performing tasks in microgravity and reduced gravity environments, and the minimum net habitable volume required to accomplish these tasks in order to prevent and reduce injuries and inefficiencies. Mockups and simulators with an appropriate level of fidelity to accurately represent the vehicle/habitat layout configuration will be key to properly replicating the vehicle/habitat configurations experienced in microgravity and reduced gravity environments. These mockups can provide insight into design and later continue to be used for training purposes. Another challenge is the verification of requirements during development when many systems are being developed concurrently – we must rely, in part, on high-fidelity computer models. For example, spacesuits in a range of anthropometric sizes and a realistic acoustic environment are generally not available for testing during development. The lack of adequate verification of the requirements during development may result in noncompliance with the requirements and adverse effects on crew during operations.

Finally, during the operational phase, there needs to be a systematic capture of lessons learned regarding the vehicle/habitat design and utilization so that ergonomic and environmental issues and impacts are identified and validated, and countermeasures and interventions can be applied.

This will require development and use of habitability and ergonomic assessment metrics, tools and methodologies.

The risk of incompatible vehicle/habitat design is broad and represented by eight contributing factors. Evidence is presented below for these factors including: 1) Anthropometric and biomechanical limitations, 2) Motor skill/coordination or timing, 3) Space and lunar visual environments, 4) Vibration and g-forces, 5) Noise interference, 6) Seating, restraints and personal equipment, 7) Visibility/window design & placement, and 8) Vehicle/habitat volume/layout. These contributing factors were derived from the Department of Defense Human Factors Analysis and Classification System (Department of Defense, 2005), the industry standard for human error categorization The evidence about risk reduction presented in this report is organized around eight types of causal risk factors, selected from the HFACS categories of error (Wiegmann & Shappell, 2003). This classification system attempts to identify the point or points in a causal chain of events that produced an accident, typically with behavior identified as an error after the fact. This approach focuses on explaining events after they happen, and providing a causal chain in this explanation.

Levels of Evidence

The levels of evidence presented in this chapter are based on the Levels of Evidence in the NASA Risk Management and Analysis Tool (RMAT). These are: Case Study, Expert Opinion, Terrestrial Data, Expert Data, and Modeling Spaceflight Incidence. Evidence presented in this chapter encompasses lessons learned from 50 years of spaceflight experience and ground-based research related to the risk of incompatible vehicle/habitat design. Portions of the evidence consist of summaries of subjective experience data, as well as non-experimental observations or comparative, correlation, and case or case-series studies. It should be noted that some evidence in this chapter is derived from the Flight Crew Integration (FCI) International Space Station (ISS) Crew Comments Database. Although summaries of ISS crew feedback are presented as evidence, the database is protected and not publicly available, due to the sensitive nature of the raw crew data it contains. Data is also presented from Crew Office approved Space Shuttle Crew Reports. These reports are not publicly available.

Evidence

Contributing Factor 1: Anthropometric and Biomechanical Limitations

Anthropometric and biomechanical limitations are factors when the size, strength, dexterity, mobility or other associated limitations of the human body create an unsafe situation. While human factors risks that end up resulting in catastrophic human error such as flight accidents solely due to anthropometry and biomechanical limitations are somewhat difficult to quantify, studies have shown that poor consideration of physical body, shape, size, and exertion capabilities, as well as poor clearances around the operator by the surrounding work interfaces could lead to severe injuries (amputation) as well as loss of life (Konz & Johnson, 1999).

A study by Scheuring, Mathers, Jones, and Wear (Scheuring, Mathers, Jones, & Wear, 2009) constructed a database of in-flight musculoskeletal injuries over the entire United States space program. As part of that effort, when available, injuries categorized the type, mechanism, and causality. The data was obtained from multiple sources including: post-flight medical debriefs, the Lifetime Surveillance of Astronaut Health (LSAH) medical record database, and the JSC medical records. A total of 369 in-flight musculoskeletal conditions were identified. The highest number of musculoskeletal injuries involved the hand, back, and shoulders with abrasions and contusions being the highest type of injury. While the causality information was limited, injury causes were attributed to crew activity, EVA suit, and exercise equipment and to a lesser extent Launch and Entry Suit (LES)/Advanced Crew Escape Suit (ACES), experiments, EVAs, and egress. There was no specification of whether egress injuries occurred while suited or unsuited. From the types of crew activities that could be identified by Scheuring, et al., many are related to habitat design, as described below. Types of crew activity injuries included impacting structures (12 injuries), stowing equipment (8 injuries), translating through the spacecraft (8 injuries), repairing equipment (7 injuries), abnormal positioning (6 injuries), transferring equipment (5 injuries), restraint (5 injuries), and donning suit (3 injuries). See Figure 1 taken from the Scheuring et al. report. Habitat design could help reduce a number of these types of injuries with good design. Crew activity type details were listed as "unknown" for over 16 musculoskeletal injuries. So it is possible that the number of habitat/vehicle design attributable injuries is under-represented. Thus, there is a need to modify onboard crew health and safety monitoring with additional "memory joggers" to inquire about the causes of the injuries (when and if they happen) more systematically. This information should somehow be made available to designers when it could improve equipment and habitat designs and improve task flows.

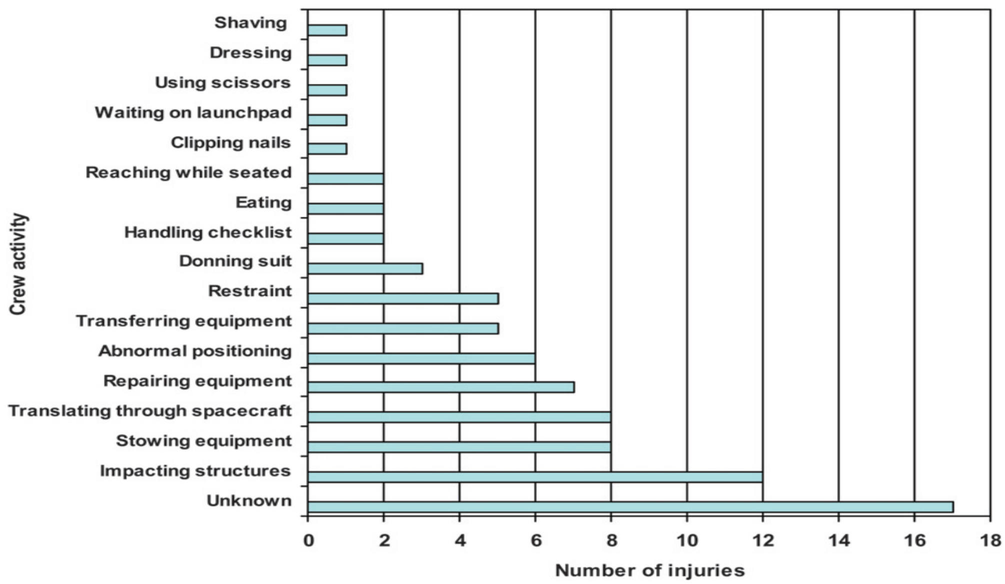

Figure 1: Types of crew activity causing in-flight musculoskeletal injuries throughout the U.S. space program

Another injury that may surface in the crew is Repetitive Stress/Strain Injuries (RSI). Repetitive stress or strains over extended periods of time, have long been an issue identified that can affect the quality and quantity of productivity. The term "Repetitive Strain Injury" or RSI is a broad categorization encompassing a wide variety of injuries. Repetitive strains are not always immediately apparent. The design of tools and workspace can be the cause of some of these types of injuries. In a chapter describing hand tools and devices, Sanders and McCormick (1993) describe human factors issues relating to cumulative traumas and repetitive strain. They mention that strains or injuries may not show up in accident injury reports, but as reduced work output, poorer-quality work, increased absenteeism, and single-incident traumatic injuries. Human factors can contribute to the reduction in RSI through tool redesign and training of proper tool use. The authors emphasize that the tools should not be designed in isolation. It is important to evaluate and design the proper workspace, workstation, and task flow. In the space environment, potential unsuited tasks could be impacted if the human interfaces of the workstation design are not considered; science gloved-box operations, robotic operations and some maintenance activities require awkward postures and may impact tool design. Information is still being sought to determine if there are any documented cases of RSI related space injuries that are attributable to the physical space environment.

Also, studies have shown that repeated exposure to poor postures, constrained postures, and difficult and sustained moderate exertion can also lead to irreversible cumulative trauma disorders (CTDs). Some of these persisting, poor physical ergonomic conditions could further be exacerbated in the space program due to a significant lack of knowledge about the impact of wearing a pressure suit, having to perform simple to complex tasks under pressurized conditions, possibly in a de-conditioned state due to exposure to microgravity, and the concomitant reduction in one’s ability to perform physical exertions. Unfortunately, unlike an industrial setting where numerous studies have been conducted to identify the impact as well as severity of impact to worker performance, the space program, even today, lacks a sufficient amount of physical ergonomics knowledge that can be used to reduce potential risks and loss of life or amputation via meaningful requirements. Thus, there exists a significant void in terms of determining the potential physical risks that await a space crew as well as the necessary remediation procedures/rules/requirements.

The identification of these limitations relies on the selection and definition of the appropriate reference user population. Selection of the appropriate reference anthropometric population is very critical in designing a human-system interface (whether it is a habitat, a workspace or equipment). Traditionally, designers use pre-existing data as a reference in their design, evaluations and analysis, rather than collecting their own. There are a number of anthropometric databases available such as ANSUR - 1988 US Army Anthropometry Survey (Gordon, Churchill, Clauser, Bradtmiller, & McConville, 1989) , CAESAR - Civilian American and European Surface Anthropometry Resource (Robinette, Blackwell, Daanen, Boehmer, & Fleming, 2002) and NHANES - National Health and Nutrition Examination Survey (Ogden, Fryar, Carroll, & Flegal, 2004). However, these databases were collected on a specific subset of the population and may or may not be appropriate to use for the highly specialized, uniquely trained spaceflight crewmember population. The space program currently uses a modified ANSUR database population that is height-adjusted and age-truncated to reflect the current and future astronaut population (NASA, 2009a). Data sources related to range of motion and strength are task-specific and there are numerous studies to choose from to address/accommodate a particular user-selected criterion.

The allowable crew anthropometry is a programmatic decision and is out of scope for human factors research. In the 1990s, during the Soyuz vehicle missions, some astronauts were barred from flying on the Soyuz for being “too tall” or “too short” (Watson, 2007). This type of limitation was addressed and the Soyuz was modified to accommodate the U.S. astronaut corps in later years. Once the appropriate anthropometric dependent population is selected, then the task is to determine the impact of wearing a pressurized suit, working and operating in a confined environment while being exposed to excessive vibrations, g-forces, and restrictive interfaces such as seats, consoles, connectors, etc.

When anthropometry and biomechanical capabilities and limitations are not properly understood and considered in design, poor crew performance, injuries, and risk to the mission success are possible. Spaceflight experience (Extravehicular activity (EVA) injuries, crew de-selection), and terrestrial data (laboratory studies of EVA suit biomechanical limitations, injuries during EVA training in the Neutral Buoyancy Laboratory) suggest that lack of proper consideration of anthropometry and biomechanical limitations during EVA suit design and planning has resulted in additional EVA training and longer on-orbit EVA operations.

Microgravity Effects

The physiological effects of microgravity, such as spinal elongation, present additional challenges, particularly for long-duration crews. These effects directly impact anthropometry and strength of the crew, and indirectly impact the available range of motion of a crewmember.

The physiological effects of muscle atrophy, bone density loss, and fluid shifts differ depending on the mission duration and amount of onboard exercise. A crewmember's de-conditioned state is directly correlated to the duration of their stay in a microgravity environment. The ergonomic impacts of the physiological effects are not well understood, and bed rest studies are currently under way to simulate a microgravity environment to study the effects of exposure to microgravity (Hutchinson, Watenpaugh, Murthy, Convertino, & Hargens, 1995; Styf et al., 1997).

Spinal elongation is the straightening of the natural curvature of the spine in microgravity. This occurs due to fluid shifts in the body and the lack of compressive forces on the spinal vertebrae. As the natural curvature of the spine straightens, an increase in stature occurs. A study performed during Skylab indicated that the stature of astronauts increases by approximately 3% after the first two days in microgravity. The Skylab study involved only four subjects. An additional Apollo-Soyuz Test Flight study (Brown, 1976) was consistent with the Skylab study (Brown, 1975; Thornton, Hoffler, & Rummel, 1977; Thornton & Moore, 1987). Because all of the growth is attributed to changes in spinal length, 3% of the person's stature has been added to the length of the spine (Churchill, Laubach, McConville, & Tebbetts, 1978), and this has driven current requirements in Human Systems Integration Requirements (NASA, 2009a). Research has recently been completed onboard a series of Space Shuttle missions to determine changes in seated height as a result of microgravity. Results will help identify potential improvements to future vehicle architecture (in particular, seats) and thus potentially increase safety and efficiency of future missions. More in-depth research should be conducted to better understand how the body changes over time in microgravity.

Changes in body anthropometry have ramifications across all aspects of a design, both for the vehicle and suit. If parts of the body swell or shrink, the individual is no longer sized appropriately in the suit, increasing the likelihood of fatigue or chances of injury during suited operations. Similarly, the fit of individuals relative to the vehicle also change which causes potential discomfort and restrictions. Thus, current design requirements may not be adequate to ensure long-duration crew accommodation. For example, changes in crew anthropometry can contribute to occupant protection problems if the safety hardware no longer fits as designed. Operator errors may occur if the biomechanical performance of the crew has been degraded due to muscle atrophy or other unknown in-flight physical changes.

Spaceflight conditions and their effects on crewmember characteristics such as posture can strongly influence the design of hardware such as suits. Data on spaceflight crew-postural changes are limited. Earlier Skylab and Shuttle studies have shown that the crewmembers often take up a semi-crunched (curled up) posture in microgravity, called neutral body posture (NBP, Figure 2), with knees bent and hips flexed (NASA, 2011b). Weightless posture is different from any normal 1-G posture on Earth, and the body resists with fatigue and discomfort against any attempts to force it into 1-G postures or appliances consistent with 1-G postures. The Anthropometric Source Book Volume I: Anthropometry for Designers (1978) suggests these postural changes should directly affect architectural design for future missions.

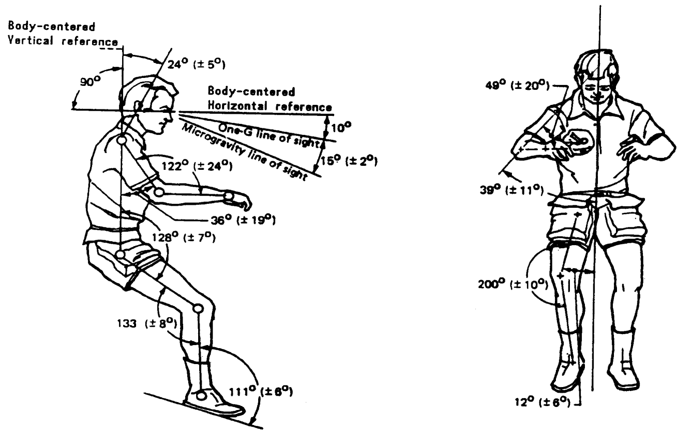

Figure 2. Neutral Body Posture

Mount, Whitmore and Stealey (2003) found that, in general, three-main neutral body postures (NBP) were exhibited by the STS-57 crew. These constituted (1) an almost standing posture (Figure 2; crew 6), (2) a slightly pitched forward posture with an extreme bend at the knees (Figure 2; crew 2), and (3) an elongated posture with a straight neck (Figure 3; crew 4 and 5). The differences in posture could be a result of the participants' athletic bearing or the type of exercise, or both, and the amount of exercise regularly performed. Other differences may come from past physical injuries or gender differences such as center of gravity. Current research on neutral body posture in the NBL (Fontaine, Ellerbeck, Dirlich, & Rajulu, 2011) indicates that variations found among subjects were significantly different than the results found in the previous study. They found that NBP may actually change depending on the task a person is doing, and hence task must be considered when using NBP for design. It should be further noted that no studies have been conducted to date to understand the impact of NBP on suited operations, and recent discussions with Mission Operations personnel indicate that the issues of NBP as well as spinal elongation may become of greater interest in future missions.

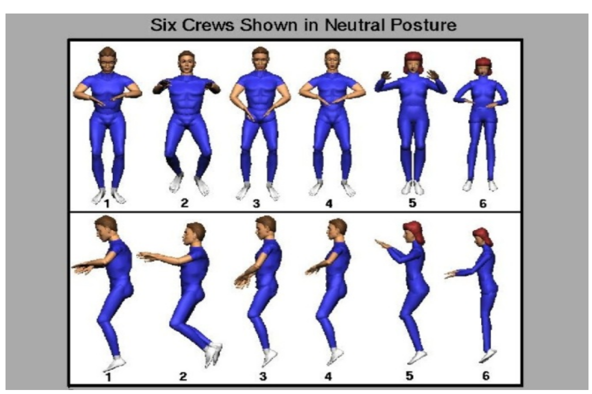

Figure 3. Neutral Body Posture of the STS-57 crewmembers.

If awkward postures are held for long periods of time, they may cause considerable damage to a crewmembers' body (muscle strain), and may compromise some physically demanding tasks during the mission. Awkward hyper-G loading may worsen the outcome. Researchers need to explore not only how the crew interacts with the vehicle during nominal scenarios, they should also explore how crew will access and troubleshoot hard to reach locations, such as behind control or service panels.

Suit Effects

One of the EVA systems is the Extravehicular Mobility Units (EMUs). As can be found in the "EVA Console Handbook" on the "International Space Station Live!" website (NASA, 2012) the ISS Joint Airlock is where EMUs are stored and maintained and allows the preparation and servicing of the EMUs before and after the EVAs. The joint airlock consists of two modules, the Equipment Lock and the Crew Lock. All EMUs are put on or taken off in the Equipment Lock where they can be recharged and serviced and where activities which require pressurization take place. Other related equipment is stored there. As part of the "powering up" of an EMU suit, a series of switches are flipped by the crew to send power down to umbilical interfaces located in the Crew Lock. At the end of these processes, the EMU will be able to provide power, oxygen, and hard-line communication for the crewmembers in the joint airlock. When the crew exits the joint airlock, the EMU begins running on battery power for the remainder of the EVA. The design of future air locks should not only be examined from the human factors perspective in order to optimally facilitate activities such as maintenance and servicing, but to also look at the time critical powering up processes and EVA tasks to ensure tasks can be completed with the available battery power limitations.

The EMU itself is known to cause performance detriments in crewmembers in comparison to unsuited operations. Capturing the effects of the suit allows for quantification of these detriments to ensure that all suited operations could be performed by all crew members without risk of injury or risk to the mission success. Unfortunately, the effects of the EMU on strength and range of motion have not been fully explored, and these are highly dependent on the overall fit of the individual within the EMU, as well as the type of EMU the crewmember is wearing.

In a 2004 study examining EVA training injuries and related symptoms in the EMU suit, it was found that hands, shoulders, and feet were associated with the most reported symptoms (Strauss, 2004). The hands had the highest reported symptom (41%), with the primary complaint being fingernail delamination (onycholysis). The cause of fingernail delamination is axial loading of the finger coupled with excess moisture in the glove. The axial loading is attributed to extended reaching and forceful grasping motions of the crewmember during training. The glove fit of individual, as well as the design of the glove itself was attributed as the cause of the symptoms/injuries.

The complaints regarding the shoulder (21% of reported) involved hard contact between the shoulder and the hard upper torso (HUT) of the suit, most often occurring when the crewmember is in a head down (inverted) position with the arms abducted from the body. Many crewmembers have experienced shoulder rotator cuff stress and strain injuries as a result. The Shoulder Injury Tiger Team was formed to explore the causes behind these injuries, and determined that the EMU Planar HUT shoulder joint increases the risk of shoulder injuries due to its placement of the bearing relative to the body's shoulder joint (Williams & Johnson, 2003). The fit of the individual within the HUT as well as the design of the suit itself was attributed as the cause of the symptoms/injuries.

The feet also had a large portion of complaints (11%), specifically uncomfortable compression of the top of the foot and impingement of the distal toes. These complaints were attributed to problems with boot fit. The remaining symptoms recorded from the suit involved the arms, legs, neck and trunk areas, and all focused on contact causing abrasions and contusions with the related suit component. The Strauss study recommended increasing strength training for the hands and shoulder to minimize the potential for injury and also recommended optimizing or improving suit fit for all reported areas of complaint (Strauss, 2004). Thus, strength and anthropometry are critical components in the comfort and performance of individuals within the suit.

Previous studies have found sharp declines in strength for gloved performance. In a study in 2010, it was found that on average, subjects wearing an unpressurized Phase VI glove with a Thermal Micrometeoroid Garment (TMG) could produce only 55% of the force seen when they were bare-handed, and 46% in the pressurized condition (Mesloh, England, Benson, Thompson, & Rajulu, 2010, July 17 - 20). Without the TMG, gloved grip strength increased to 66% of bare-hand strength in the unpressurized condition and 58% in the pressurized condition. These effects result in reduced dexterity, tactility, and mobility during EVA missions, potentially increasing the fatigue, duration, and chance of injury to an astronaut.

The suit also impacts the range of motion of an individual, in comparison to unsuited. A mobility study was conducted in 2008 to assess the impact of the suit on functional mobility, specifically tasks the astronauts were likely to perform during a Lunar EVA (England, Benson, & Rajulu, 2008).This functional task list included such actions as walking, crawling, manipulating cargo, rotating a hatch, climbing a ladder, ingressing a recumbent seat and more. The intent was to set design requirements based on the minimum range of mobility necessary to perform tasks, saving resources as compared to requirements to supply the full range of human mobility, while suited, for any imaginable task. The results have driven current requirements in Human System Integration Requirements (HSIR) to account for the reduced mobility of the suit (NASA, 2009a).

Vehicle Effects

Not accounting for anthropometry, strength, and range of motion, vehicle and interface design may affect performance degradation in terms of high workload and increased performance time or error. This may create an unsafe environment for the crew during high-stress or time-sensitive operations. Adequate design requires a thorough understanding of crew physical dimensions, range of motion, and strength, both at the individual component level as well as the placement of the component in the overall vehicle space to allow for crew accommodation and avoidance of issues related to these conditions. The issues that arise are potentially multifaceted; they are a combination of anthropometry, range of motion or strength, or all three acting together. Thus, there is a need to ensure that components are fully examined across all potential human factors possibilities to reduce the risk to crewmembers.

A human-system interface within a spaceflight vehicle or habitat can potentially lead to unintended obstructions to operations or cause accessibility issues due to the device of interest being blocked by other components, or the interface itself being poorly designed from an anthropometric, mobility, or strength standpoint. According to the FCI ISS Crew Comments Database, previous spaceflight crewmembers have encountered difficulties accessing racks due to complicated mechanisms required in order to open and close rack doors. In one particular case, a closure mechanism includes thin metal slits in three places and leather straps that have to be pushed through like a shoelace. This interface requires pliers to pull the leather straps through, and can still lead to gaps in the rack door despite the complicated closure mechanism. In another example, some fasteners onboard are difficult to access, and require awkwardly reaching around a panel to interface with them, which, in turn, may lead to difficulties in removing the fasteners. In some cases, performance of tasks such as the disconnection of cables may be hindered due to constraints related to accessibility or obstructions within an area, because there may not be enough room to apply enough strength to complete the task. Some rack areas onboard ISS are difficult to access and can impede viewing what one is trying to access when performing tasks such as maintenance. Unavoidable volume constraints onboard can also lead to difficulties accessing and actuating interfaces such as quick disconnects (QDs), especially when they require high force or torque to operate or manipulate. These and other issues can potentially result in increased task duration, inability to perform the task, as well as crew injury as a crewmember contorts their body to manipulate the interface.

Improper actuation force, especially with potentially deconditioned crew, is also of concern for spaceflight operations within a vehicle or habitat. According to the FCI ISS Crew Comments Database, previous spaceflight crewmembers have indicated the importance of assessing how much force is required for actuating switches. More force than a crewmember expects may be required to mate both contacts on a switch. If a crewmember cannot operate a device, it can potentially create an unsafe environment in the worst case scenario and, at the very least, will cause increased performance time or error as the crewmember struggles with the device or enlists the help of a second crewmember to operate it.

The wear and tear on components, as they are repeatedly used by the crew, is also of concern. According to the FCI ISS Crew Comments Database, previous spaceflight crewmembers have indicated locker doors and panel interfaces may come out of alignment and stick and be difficult to open. Some panels get stuck and require additional and unnecessary tools to open them. Devices must be made robust enough to withstand expected use, or else crewmembers will be unable to operate them or will have to devise alternative means of operating the device. The wear and tear on the human-system interface can lead to the crewmember operating it in a less-than-ideal fashion, increasing the potential for crew injury, equipment or interface damage, as well as increasing performance time and error rates while completing tasks.

In general, strength, anthropometry, and range of motion issues must be considered in the overall and integrated design of spaceflight vehicles, habitats and interfaces. Devices and interfaces must be built to withstand forces imposed by crewmembers as well as accommodate the range of crewmember anthropometry. Conversely, crewmembers must be well trained to be aware of the techniques and strength required to operate a device or tool, to reduce the possibility of device failure from unintended use or crew injury. According to the FCI ISS Crew Comments Database, previous spaceflight crewmembers have indicated that some maintenance tasks require or were helped by having 2 people performing the tasks due to strength, anthropometry, and range of motion constraints, or simply to add efficiency to the task.

Consideration must also be made for crewmember size and potential impacts to task performance if they are too large or too small. For example, some crewmembers may be smaller in anthropometric dimensions, which allows them greater reach or grip capacity into confined spaces while performing maintenance. In the case of some interfaces, crewmembers have felt they were applying too much force or strength. If a crewmember's hand is too large they may not be able to achieve good grip, and additional or potentially unnecessary tools may be required to interface with a connector or device. Whenever possible, crewmembers should also be provided with a clear indication of how much force is required to be applied to hardware and interfaces. Efforts must be made to avoid any confusion about the amount of force required of a crewmember to complete tasks to allow for successful and safe task execution. Tools provided to crewmembers must also accommodate the appropriate amount of force required to complete tasks while avoiding stripping bolts or damaging hardware.

Contributing Factor 2: Motor Skill/Coordination or Timing

Motor skill, motor coordination or timing are contributing factors to the risk of incompatible vehicle/habitat design when an individual lacks the required psychomotor skills, coordination or timing skills necessary to accomplish the task attempted.

Gravity plays a major role in development and execution of human motor behavior. When we experience microgravity, the laws of motion of our body and the objects in the environment we wish to interact with change. These environments create distortions of orientation and posture, as well as disruptions of certain aspects of limb proprioception and oculomotor control (Lackner & DiZio, 2000). Furthermore, the ability to intercept or avoid a moving object is impaired. The ability to anticipate the trajectory of a moving object is based on sensorimotor functions that were developed in a 1-G environment (Rushton & Wann, 1999). These skills become increasingly important as we extend periods of microgravity with longer duration missions on the ISS, to an asteroid or Mars. In addition, as crewmembers become increasingly deconditioned, detriments to their motor skills are possible, affecting interaction with displays and controls as well as with other subsystems. Crewmembers may not have the fine motor skills required to perform critical tasks in a timely fashion. These declines in crew capabilities need to be considered up front during design whenever possible, but first we must have a good understanding of the effects of long-duration spaceflight on motor skills, and what mitigations might be most appropriate.

The idea that microgravity would have an influence on perceptual-motor performance seems valid, given the influence gravity has on the vestibular and muscular systems (Lackner & DiZio, 2000). A number of sensorimotor functions depend on gravity, such as postural balance, hand-eye coordination, and spatial orientation (Clément, 2007). The vestibular system responds to linear and angular accelerations of the body; these responses then become integrated with visual and some esthetic inputs to generate the appropriate muscle movements in relation to a goal in the environment. During a mission to another planetary body, these sensorimotor functions must adapt to a number of different microgravity environments. During these periods of adaptation, sensory inputs could be misinterpreted, leading to incorrect responses of the human body. These incorrect responses could lead to errors that could potentially cause loss of mission or threats to crew safety.

For example, one cosmonaut during an 8-day mission on *Mir* found performance impairments with a tracking task using a joystick during early phases of the mission. A second cosmonaut during a 438-day mission on *Mir* found similar results. However, because of the number of confounds, microgravity could not be established as the sole contributor to decreased performance (Manzey, Lorenz, & Poljakov, 1998; Manzey, Lorenz, Schiewe, Finell, & Thiele, 1993, 1995). In an attempt to isolate the role of microgravity, a third cosmonaut during a 20-day mission on *Mir* performed the same tracking task, but with the addition of an aiming component. Impairments were attributed to the influence of microgravity by an underestimation of mass of the arm and hand (Manzey, Lorenz, Heuer, & Sangals, 2000).

An aiming task using a joystick or a trackball to move a cursor was performed by 4 astronauts on an 8-day space shuttle mission (STS-89). Longer movement times were experienced for microgravity vs. baseline ground movement times (Newman & Lathan, 1999). In contrast, two studies with 6 astronauts during a 16-day Neurolab shuttle mission (STS-90) involving visual-motor coordination, failed to reveal performance decrements that could be attributed to microgravity (Bock, Fowler, & Comfort, 2001). This may be due to the fact that the astronauts were stabilized with a harness during the task. A study of 7 cosmonauts on *Mir* found that ability to see the hands vs. not see the hands during a tracking task failed to influence performance (Mechtcheriakov et al., 2002). The researchers concluded that the failure to find an effect of vision was evidence against a role of microgravity, and instead suggested that slowing of the movements was an adaptive response to preserve accuracy in weightlessness or because of body instability in the lateral plane of the body. An experiment using 5 astronauts (STS-117 and 118) attempted to discern the role of cognitive overload and microgravity using a Fitts' law model to measure performance in a tracking and aiming task with either a single- or dual-task component (Bock et al., 2001). Results found decrements in performance only with the dual-task paradigm, suggesting cognitive overload, rather than microgravity, was the primary culprit in decreased sensory-motor performance.

Coordinated or timed movements rely upon information gathered by the visuo-motor system. Studies have shown that people are sensitive to patterns in gravitationally-governed events by their ability to recognize the dynamic properties of that event from the visually specified motions (McConnell, Muchisky, & Bingham, 1998). This suggests that by perceiving the kinematics of an object, people have intrinsic knowledge of the underlying dynamics of the object governed by physical laws of gravity (Runeson & Frykholm, 1983). When these laws become violated, such as in microgravity, this could lead to inaccurate perception of the dynamics of the object (e.g., moving or falling objects, or collisions between objects) and any coordinated or timed actions of the user.

This hypothesis was tested on a Neurolab experiment in which astronauts caught a projected falling ball with one of three randomly sorted speeds (McIntyre, Zago, Berthoz, & Lacquaniti, 2003). In normal gravity (1-G), a peak of anticipatory biceps activity occurs in about 40 ms, as well as a forearm rotation upward to meet the ball and stiffening of the hand. These events can tell us when the brain expects the ball to arrive. Results showed that the timing of an Electromyogram (EMG) peak and forearm activity started too early in zero-G, with the limb movements stopping and in some cases reversing once the error in anticipation was perceived. This suggests that neural responses can be corrected by updating estimates of time-to-contact based on visual feedback.

In summary, there is obvious disagreement among results found in the various studies on motor performance in microgravity. All the studies found that movements are slower in microgravity, but it is unclear whether this is the product of sensory-motor deficits due to microgravity or cognitive overload due to environmental stressors. A final suggestion is that slowing of movements is simply an adaption strategy used by the motor system to optimize inter-limb dynamics and to preserve movement accuracy. In microgravity environments, movement of the limbs produces counter-forces in other parts of the body. It could be that compensation for these counter-forces contributes to slower movements by adjusting muscle stiffness.

Regardless of the mechanism, the point is clear that further research is needed to better understand the processes involved in optimal movement control in extreme environments. During short-term missions, accuracy and speed of movements has generally not been a problem. However, as we venture further from Earth with longer mission durations, these motor decrements could be an issue. Unless these processes are better understood through research, the development of appropriate countermeasures cannot be undertaken.

Contributing Factor 3: Space and Lunar Visual Environments

Conditions related to space and lunar visual environments are a contributing factor to the risk of incompatible vehicle/habitat design when weather, haze, darkness, dust, smoke, etc. inside or outside the vehicle/habitat restricts the vision of the individual to a point where normal duties are affected. Poor visibility conditions are a likely contributory cause for error, injury, or poor task performance. Lighting is critical to spacecraft vehicle and habitat design as visual perception is the primary method that allows crewmembers to obtain information about their physical environment. Spacecraft lighting systems should be designed to promote efficient safety, task performance and wellbeing as well and meet appropriate requirements for optical imaging within the environment. Lighting engineering may involve some difficult tradeoffs in meeting these needs within power constraints and physical restrictions on light source, vehicle and habitat volume constraints, and operator tasks and their locations. Mission objectives must be considered when addressing these tradeoffs.

Lighting is an environmental factor that pertains to both inter- and extravehicular activities. According to the FCI ISS Crew Comments Database, overall illumination onboard ISS is satisfactory while some modules provide better lighting and visual environments than others. Optimal lighting is important to allow for successful task execution. Considerations must be made for things like stowage which can block and impede lighting within modules. Activities that are completed behind racks and in out of the way locations often require the use of additional portable lighting. Accommodations and appropriate lighting hardware provisions should be made as appropriate. The design and placement of lights and lighting schemes within modules must also be carefully considered for ISS modules and future vehicles and habitats. Some crewmembers have recommended that lighting should always be exposed and oriented vertically. Crewmembers also have reiterated the importance of providing lighting spares on orbit to accommodate lights as they burn out.

Lighting may impact the ability to access equipment and information. For example, according to Space Shuttle Crew Reports, during a Reconfigure Orbiter Communications Adapter (OCA) Downlink Rate procedure, one crewmember inadvertently selected "BYPBK" instead of "BYPFR" on the MUX BYPASS rotary knob on Panel LlO. This affected photo/TV equipment and other Payload General Support Computer (PGSC) equipment. The crewmember attributed this mistake to the fact that the rotary knob was poorly lit. This highlights the importance of ensuring that displays and controls are properly lit to avoid any inadvertent mistakes or impacts to readability and use.

A nighttime-lighting analysis studying the visibility at night of the SRMS (Shuttle Remote Manipulator System), OBSS (Orbiter Boom Sensor System) and the Space Shuttle tile area during a proposed automated tile scan on ISS Flight LF-1, Flight Day 2 was performed by the Graphics Research and Analysis Facility at Johnson Space Center. It was assumed that viewing of the joints for the entire SRMS/OBSS was necessary, as was clearance assessment of the arm to Orbiter. To achieve this, the available lights and cameras had to be panned and tilted to various areas of joints and wings to allow an entire view of the critical areas. The preliminary look at nighttime lighting options available during the automatic tile scan revealed that there was not a single light or combination of lights that would allow the entire scene to be illuminated adequately for the cameras. The payload bay lights only aided viewing of the arm directly above the payload bay. When the SRMS/OBSS is primarily off the port or starboard side, only the payload camera light emitting diodes could be used. This required the camera to be pointed where the light is and, generally, can only illuminate one joint or section of the arm or wing at a time. The payload bay doors blocked the view of the area of the wing closest to the payload bay. Further out, areas could only be lit in sections. The reinforced carbon-carbon material along the edge is non-reflective, and when coupled with low light, made clearance viewing extremely difficult with a color-television-camera type camera. An intensified (black and white) television-camera type in both cameras B's and C's position was preferred to aid in clearance viewing out on the wings. Antiquated technology and insufficient capabilities prevent accessibility of information under specific lighting conditions. Further investigation of alternative lighting, technologies, cameras, or resources, can increase the accessibility of information (Maida, Cross, & Tran, 2004).

Variations in the lighting spectrum within vehicle and habitat volumes and coordination of activities with daily ambient lighting variations are primary determinants of circadian rhythm synchronization. Circadian rhythm de-synchronization can result in adverse physiological and cognitive effects. Poor visibility conditions are a likely a result of lack of consideration during the development of concepts of operations or task analyses prior to System Design Review. Poor visibility in space and lunar visual environments may be due to light source failures and single device failures. Inclusion of visibility/lighting considerations during concept of operations development and system design, and during task analysis is likely to preclude costly engineering changes later in the program. Visibility and lighting issues may lead to sleep disturbances and cognitive deficits are monitored through crewmembers' conferences with flight doctors and participation in cognitive function assessments during missions. Vision restriction in the workspace may be caused by dust, smoke, inadequate lighting systems, poor window access ergonomics or other causes and can be a factor affecting normal duties. Current data collected with respect to visibility/lighting conditions consists primarily of post-mission crew debriefs. No instruments to reliably measure absolute illuminance or luminance have been flown onboard the Space Shuttle or ISS.

Contributing Factor 4: Vibration and G-Forces

Vibration and g-forces are contributing factors to the risk of incompatible vehicle/habitat design when the intensity and duration of vibration and acceleration are sufficient to impair visual perception and spatial orientation, and adversely affect the performance of normal duties. Crewmembers will experience vibration and elevated G-loads during launch, launch abort, and reentry. These are all very dynamic periods of flight during which timely and accurate crew response is essential to mission success. The impacts on performance will depend not only on vibration and G-loading, but also on launch/reentry vehicle design, required crew operations, and interface design.

An environmental condition such as vibration or G-forces can affect visual and motor performance (Sanders & McCormick, 1993). There is currently little to no data available to quantify human visual performance or cognitive effects under high vibration combined with G-loading in the G_x (i.e., chest-spine) direction. Existing data on the magnitude and frequency of vibration from Space Shuttle and previous manned programs are incomplete.

Vibration may directly cause injury via mechanical stress to internal organs and musculoskeletal structure or limb flail resulting in impact with cabin equipment and adjacent crew. Vibration may impair visual acuity via disturbances to occulomotor control systems, hamper accurate limb control via proprioceptive disruption and biomechanical feed-through, and may also cause incorrect perception of body and body-part orientation. Vibration may also impede speech production via biomechanical feed-through, and hamper audition because of vibroacoustic noise. Severe and unexpected vibration may also have a cognitive impact. Prior program early indicators of flight vibration problems include flight test (e.g., Saturn 502 April 1968) and system analyses (e.g., Ares-Orion Thrust Oscillation, 2007-2009), both of which triggered ground tests with crew, and extensive modification of the launch vehicle. NASA's crew and non-crew ground test experience is limited to 11-Hz Titan-II Pogo oscillation for Gemini and 12-Hz Ares-Orion thrust oscillation for Constellation, both in the chest-spine direction. Because of the absence of comprehensive and validated crew performance models for general vibration-plus-G environments, any newly predicted or observed flight vibration profiles will necessitate new HITL testing.

Visual and manual performance deficits under vibration in the 1-G Earth environment as well as health risks from prolonged vibration exposure in the workplace have been widely documented, but primarily for an upright, seated posture (Griffin, 1990).Our understanding of the effects of combined vibration plus g-loading on human performance, specifically for the semi-supine posture of the space launch environment (i.e., gravity in the chest-spine direction), is limited to 11-Hz Gemini Pogo oscillation (Vykukal & Dolkas, 1966) and 12-Hz Constellation (Adelstein et al., 2009) point-design evaluations, both of which were conducted only for a 3.8-G_x bias.

Unlike the extensive epidemiological observation for chronic low-amplitude exposure supporting current international occupational health guidance, health guidance for brief, high-intensity vibration exposures of the type expected for space launch is founded on very limited set of laboratory data from the early 1960's that were obtained only for a 1-G bias. Elevated G-loading is known to alter the biodynamic resonances of different body parts and internal organs, which therefore may alter susceptibility to injury in unknown ways.

Recent human performance studies have demonstrated that vibration can interfere with the crew's ability to perform critical mission functions including reading and using modern displays and controls. These studies also demonstrated that performance deficits may persist after vibration ceases. Moreover, deconditioning due to prolonged exposure to space environments and microgravity may exacerbate performance deficits due to even modest vibration and G-loading.

When subjected to multiple whole body vibration (0, 0.15, 0.3, 0.5 and 0.7 g_x) and sustained 3.8-G_x ascent acceleration in the Ames 20-G centrifuge, test subjects demonstrated significant degradations in both task error rates and response times at 0.5 and 0.7 g_x for 10-point and at 0.7 g_x for 14-pt font displays while performing numerical display reading tasks (Adelstein et al., 2009). Based on this research, the researchers concluded that elevated vibration combined with the G_x loading expected during the dynamic phases of Ares-Orion flights could significantly degrade human vision, visuomotor, and sensorimotor function, and subsequently impede the safety and efficiency of vehicle operations. Specifically, such launch loads may lead to decreased static visual acuity, decreased visual sensitivity, increased reaction/response time, decreased field of view, eye movement impairment, and increased workload.

Similarly, Beard et al., (2009) examined whether a simulated spaceflight environment that included vibration and up to 3.8-G_x ascent forces while in the Ames 20-G centrifuge would lead to cognitive deficits. The Spaceflight Cognitive Assessment Tool for Windows (WinSCAT) was used to determine whether deficits occurred. They noted that altered gravitational environments can create spatial disorientation, visual illusions and counter rolling of the eyes, and manual control problems. While this research did not indicate significant cognitive effects via the WinSCAT questionnaire scores, it did yield significant subjective reports of physical discomfort following vibration and acceleration exposure in the centrifuge. Although cognitive effects were not observed with the WinSCAT, the researchers felt that these findings warranted the need for a tool that is more sensitive to these types of cognitive changes, and the effects of spaceflight conditions that could impact crew performance and ultimately crew safety.

Recently collected evidence is outlined in the NASA report "Influence of Combined Whole-Body Vibration Plus G-Loading on Visual Performance" (Adelstein et al., 2009) in “Risk of Sensory-Motor Performance Failures Affecting Vehicle Control during Space Missions: A Review of the Evidence” (Paloski et al., 2008). Systematic study of combined vibration plus G spanning a wide range of possible loading combinations and durations is needed in order to develop models that are predictive of human performance and health impacts as well as potential benefits of mitigation strategies. Specific engineering design evaluations, such as those reported by Vykukal & Dolkas (1966) and Adelstein et al. (2009) are limited in scope and thus are valid only for the specific design points examined. Analyses that can be traced to empirical data (i.e., validated models) will need to be conducted on a case-by-case basis to determine the cost-to-benefit trade between vehicle structural, aero-loading, propulsion design (i.e., vibration source/transmission mitigation) and human factors (i.e., displays, controls, seating and suit) design modification.

The most recent studies focused only on the Constellation Program’s Ares-I thrust oscillation. The impact of other vibration frequency, amplitude, and duration profiles is unknown. Without the benefit of additional research, the only recourse is to provide sufficient (and potentially excessive) design margins to ensure occupant health and effective performance during launch and landing, or to accept addition levels of risk.

Contributing Factor 5: Noise Interference

Noise interference is a contributing factor to the risk of incompatible vehicle/habitat design when any sound not needed to accomplish a task interferes with the individual's ability to perform that task. This factor also contributes to risks to long term crew health such as hearing loss, as well as short-term effects to hearing caused by temporary threshold shifts. High noise levels contribute to hearing loss and the inability to perform tasks that require communication, and can affect cognitive functioning. Noise can also impact the crew's ability to access information. The detrimental effects of noise increase significantly for those persons with hearing loss including presbycusis.

Data contained in the FCI ISS Crew Comments Database indicate that ISS crews rely heavily on auditory information and warnings on-orbit. A primary advantage of such auditory information is that crewmembers do not need to be looking at a display to be aware of an alarm. Generally speaking, the use of auditory information frees visual attention to attend to other tasks.
While noise exposure is an aspect of all living and working environments, the continuous nature of noise exposure from constant sources such as air handling equipment results in a relatively higher noise dosage for crews. Crew health hazards of most concern are temporary or permanent hearing loss, though other effects can be significant. When noise levels are excessive, there is a detrimental effect on face-face speech communication, speech intelligibility for radio communications and caution-warning signals, habitability, safety, productivity, and sleep (Grosveld, Goodman, & Pilkinton, 2003). The ISS acoustic environment in particular is complex and includes many types of noise-generating hardware because the ISS functions as not only the spaceflight crew's home, but also their workshop, office, and laboratory (Rando, Baggerman, & Duvall, 2005). The cumulative effects of the ISS acoustic environment manifest themselves in two forms: continuous and intermittent noise (Baggerman, Duvall, & Rando, 2004). Continuous noise results from the operation of pumps, fans, compressors, avionics, and other noise-producing hardware or systems. Intermittent noise is caused by hardware that operates cyclically, such as exercise equipment or the carbon-dioxide removal system. Some single-event intermittent noises, such as during launch or by fire extinguishing equipment, may be significantly high enough in level so that hearing thresholds are temporarily shifted for a duration far longer than the intermittent sound itself, though hearing protection is used when possible to avoid these occurrences. Noise control mitigations for spacecraft environments can be challenging and expensive to install particularly in later phases of design.

Onboard acoustics measurements in various ISS modules often exceed the ISS flight rules for noise exposure and these levels can be at 67 dBA or higher over a cumulative 24-hour period (Goodman, 2000). Issues and constraints related to the acoustics environment increase the risk of impacts on crew safety because the crew may not be able to hear cautions and warnings (C&W). Although C&W tones are usually audible, there have been a few instances when crewmembers were not able to hear C&W tones due to noise. Noise has also interfered with communication between ISS crewmembers in different modules and between crewmembers in the same module. As documented in the FCI ISS Crew Comments Database, noise has cost the crew time as they translate between modules to communicate directly. In addition, some crewmembers have reported that excessive noise has negatively contributed to their perception of ISS habitability.

For instance, onboard noise has woken up some sleeping crewmembers. These high levels of continuous and intermittent noise require the use of earplugs or noise-canceling headsets to mitigate continual noise exposure (Figure 4). Although this protection assists with decreasing detrimental noise exposure, communications between the crewmembers and between the crew and ground may be degraded. In addition, crewmembers sometimes become uncomfortable while wearing this protection (Rando, Baggerman, & Duvall, 2005).

To achieve optimal acoustic levels during spaceflight, Goodman (2003) states that the following criteria should be met: acoustic levels should not present a health hazard to the crew; they should not present any significant impact or degradation to crew performance and operations; and they should provide a habitable, comfortable work and sleep environment. The importance of addressing noise interference will become even greater as long-duration crews may be exposed to excessive noise for longer periods of time, and will also no longer have the ground team as a backup to monitor for auditory alarms or signals missed by the onboard crew due to ambient noise levels. Some of these challenges may be met by a combination of noise mitigation techniques for individual components, active noise cancellation, and the use of hearing protection devices.

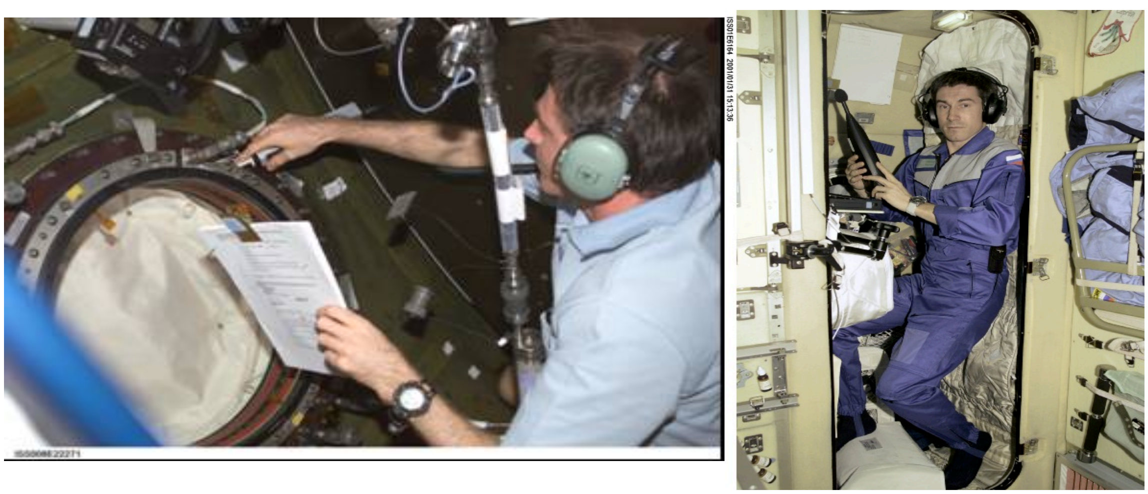

Figure 4: The two photos illustrate crewmembers wearing hearing protection devices and taking acoustic readings (Photos courtesy NASA)

Contributing Factor 6: Seating, Restraints, and Equipment

Seating, restraints and equipment are contributing factors to the risk of incompatible vehicle/habitat design when their designs do not accommodate the astronaut/user population, prevent effective and efficient performance of crew tasks within or outside the vehicle, and create unsafe situations. Spaceflight crewmembers experience long periods of recumbent and restrained static loading while seated during certain mission phases that could pose ergonomic risks of discomfort, performance decrement, and injury. Restraints may be missing, poorly designed, or too complex and time-consuming to set up/use, causing tasks performed in microgravity to be more difficult and frustrating than necessary. Equipment such as a portable breathing apparatus or sleep station may be designed without other relevant hardware components or the human operator in mind, which can create ergonomic accommodation issues during design integration and operational phases. Over extended periods of time using seating, restraints and other equipment the crew may develop Repetitive Strain Injuries (RSI). Additional information on RSI can be found in the general information of contributing factor 1 (Anthropometric and Biomechanical Limitations).

Seating

Seats must be designed to allow for and accommodate proper crewmember dimensions, adjustment capabilities, and allowances for popular body movements, reach, access, and position (NASA, 2011a). A key design challenge is provision of sufficient occupant protection without severely compromising ability of crew to reach controls and turn the head to see displays while restrained in the seat. Seat design is also often complicated by the need to accommodate suit appliances such as umbilicals, or seat-mounted devices (hand/cursor controllers).

Crewmembers are seated in a recumbent position while wearing a flight suit during launch and entry. Wearing a flight suit while restrained in a seat may affect anthropometry significantly, and recumbent seated anthropometry can differ from standard upright seated anthropometry. These considerations are critical for optimized space vehicle design, and when considered early, provide for lower design retro-fit or redesign costs (NASA, 2011a). When seating is designed correctly, vehicles are capable of accommodating a more diverse crew, performance is optimized, and safety is increased.

There is a risk of excessive crew discomfort during long-duration seated periods due to the seated posture and lack of lumbar spine support in vehicle seats. During some early human-in-the-loop (HITL) evaluations for the Constellation Program's Crew Exploration Vehicle (Orion, now Multipurpose Crew Exploration Vehicle-MPCV), several test subjects complained about lower back discomfort and numbing of the feet and legs while seated in the mockup seats for long-durations. This could be a problem for most crewmembers during all pre-launch activities. Paresthesia resulting from the long-duration static seated posture could inhibit emergency egress, endangering the crew. Also, excessive discomfort can cause an increase in workload, which could result in an increase in task error rates and a decrease in task performance.

Another seat-related issue occurred during an Orion Crew Impact Attenuation System (CIAS) evaluation. The evaluation indicated that although seat design requirements had been met, if the commander and pilot seats were configured for crewmembers with short sitting heights and medium to large buttock-to-popliteal dimensions, there was insufficient clearance for ingress or egress of the seat. In this seat configuration, ingress/egress space available was reduced by the close proximity between the seat pan and other cockpit vehicle hardware. This example highlights two important risks. First, it continues to show how individually designed components can meet requirements when tested separate from the system, but fail to meet the final design intent when integrated with the human and hardware system. Second, this example illustrates issues with the way human accommodation and population variation is typically handled during the design process. Recently, digital humans have become a standard tool to quickly and inexpensively assess how a design will accommodate users. A typical method used for this assessment is to place only minimum and maximum manikins, representing the population of interest, into the virtual space so that reaches, clearance, and interactions can be calculated. This min/max modeling method was used for clearance calculations in the case of the Orion ingress/egress space, but since the clearance issues only appeared for specific portions of the population, they were not identified in the analysis. If digital human modeling is not coupled with HITL evaluations, some of the integrated system design issues may not be discovered until late in development when changes are very costly. In this example, early Orion HITL evaluations clearly demonstrated their value-added in addition to model-based analysis. Another challenge with the use of digital models is the lack of fidelity and insufficient representation of the astronaut population and the environment (e.g., micro-G, partial-G, hyper-G); these are areas that need research attention going forward.

Restraints

In a microgravity environment, body posture is altered. Although some tasks can be performed while free-floating, most tasks require some level of restraint. A number of general-purpose restraints (e.g., handrails, foot loops) have been used within and outside the ISS. General-purpose restraints include very simple pieces of hardware that can provide minimal restraint for a number of different types of tasks. Currently onboard the ISS, crewmembers often restrain themselves by looping their feet, toes or arms under existing handrails for short duration tasks. Handrails are an essential restraint and translation aid onboard ISS that offers a simple design solution to accommodate crewmembers' need to restrain themselves while performing short duration tasks. Crewmembers use handrails to aid in navigation throughout vehicles/habitats. According to the FCI ISS Crew Comments Database, crewmembers encourage maintaining minimal and consistent design whenever possible for restraints used on a daily basis to ensure they will accommodate a wide range of tasks and task locations.

Crewmembers have reported that once they are acclimated to the microgravity environment, restraints can become less important. According to the FCI ISS Crew Comments Database, acclimation to translating along pathways in habitats such as ISS is crew dependent and can take many weeks to completely achieve. During this acclimation period, crewmembers rely more heavily on handrails placed along translation paths and while navigating throughout pathways within ISS. The use of handrails as a translation aid to navigate vehicles/habitats tends to diminish as a crewmember's duration on orbit increases. However, restraints are especially important for tasks that require the crewmember to remain in one stable posture for an extended period of time (DeSantis et al., 2011). Previous spaceflight crewmembers have emphasized the importance of restraints being designed to accommodate the operational requirements, location and number of operators for a given task. For tasks such as teleoperation, science glovebox operations and robotics operations, special restraints that offer greater stability may be required to optimize operations. For example, in order to control Robonaut, a humanoid robot astronaut, crewmembers must be stable to avoid any inadvertent movements that would be misinterpreted as a robot command. For science glovebox and robotics operations, restraints may assist in accommodating postural limitations and visual restriction which can occur while performing these types of tasks in microgravity (DeSantis et al., 2011).

The necessary volume for task operations is an important consideration when designing unique restraints for specific tasks. Restraints have been specially designed for robotics operations in constrained volume areas such as the Cupola. However operations in areas like the Cupola may be difficult with three people inside. Even two crewmembers can be cumbersome depending on the tasks being performed and the way people are situated. In this case, design considerations for characteristics such as crew height should be considered, and restraints for these operations may not even be necessary for taller crewmembers. For the robotics workstation in the US Lab, the height of the workstation itself can be easily adjusted, so the height of the crewmember is not an issue.

Another important consideration is the ease of setting up and removing restraints. Some crewmembers feel that you absolutely cannot perform robotics operations in the Cupola without foot restraints or foot plates since the Cupola is located over a hatch area and there is nothing to hang on to. Restraints may also be occasionally needed by some crewmembers while taking photos in the Cupola due to difficulties experienced while using two hands to take a picture. Moving bulkier restraints or portions of a restraint out of a working volume like the Cupola to accommodate more people within the volume during operations may be cumbersome. For example, the Cupola restraint provided for robotics operations has multiple components, which allow for some additional options to accommodate different crew preferences.

Consideration should also be given for exposed cooling lines or cables that are not intended for use as handholds, but are at risk for inadvertent use and damage over time with use as hand holds by crewmembers due to their location within a space. Labels may not prevent grabbing these components when rushing into a space, but they might increase awareness. A slow air leak onboard ISS illustrates the potential risk. In 2004, two ISS crewmembers and flight controllers located the "apparent cause of tiny pressure decay on the ISS to a braided flex hose that is part of the window system in the U.S. Destiny Laboratory" (Figure 5. A probable cause for the leak listed in some reports (Oberg, 2004; Wilson, Coffey, & Madaras, 2008) is fatigue damage to the flex hose from astronauts inadvertently using the hose as a handhold while viewing out the Destiny 20" window. The hose extends out like a handhold and is in a location where handholds are needed – thus the problem.

Figure 5: The photos illustrate inadvertent use of flex hose as restraints and mobility aids (Photos courtesy NASA)

Experience with ISS has shown that restraints that are overly complex, difficult, or time-consuming to set up or get in/out of, will not be used by the crew. If well-designed restraints are provided, and if workstation/equipment design and task procedures are optimized for the 0g environment, crewmembers' work capabilities can often approach their capabilities for performing tasks on Earth.

Equipment

Spaceflight short- and long-duration crewmembers are provided with a large amount of equipment to assist with the performance of daily tasks. Equipment can include hardware and tools, computer and network equipment, exercise and medical equipment, and other habitability hardware. Optimized design of equipment is essential to ensure adequate workload and usability of equipment. If equipment is not designed to be usable by all crewmembers, the likelihood of errors or the inability of the crew to complete a task in a timely manner increases.

As documented in the FCI ISS Crew Comments Database, some ISS hardware items and tools do not have common or consistent interfaces. For example, onboard, a mix of metric and English units of measure is used because ISS hardware and tools are designed by U.S. and international partners; no standard was enforced. In addition, some hardware items require unique tools. This can lead to decreased efficiency and negative performance effects.

Accessibility of equipment and tools is also an important consideration within larger habitats. Consistent and efficient labeling of hardware and tools helps to optimize the management, stowage and use of tools. The inventory, stowage and management of tools must also be addressed continuously to avoid complications related to lost tools or a lack of necessary and frequently used tools. In addition, spaceflight crewmembers may prefer and need multiple ways to carry individual tools. Some crewmembers may feel pants pockets don't always accommodate tools properly and prefer carrying individual tools in fanny packs while others do not.

Equipment such as connectors and fasteners are often a concern on orbit. According to the FCI ISS Crew Comments Database, while necessary to restrain panels, lockers and racks, some connectors and fasteners may be difficult to actuate or require a particular tool. Some are difficult to mate. Some of the connector interfaces break over time with use, like d-rings, and require additional tools to actuate the broken fasteners. Dzus fasteners are difficult to use, and crews have cautioned they should not be used as fasteners on any panels that contain emergency equipment to avoid delaying or prohibiting access to this necessary equipment.

Over ten years of life onboard ISS has revealed the importance of crew sleep quarters and individual private space for long-duration missions. According to the FCI ISS Crew Comments Database, previous spaceflight crewmembers have indicated that crewmembers' sleep quarters provide necessary and valued individual space for sleeping and private activities such as working and communicating with family and loved ones via email and phone. Existing crew quarters provide privacy, noise and radiation protection, and ventilation control within the space. Crewmembers routinely emphasize the importance and psychological benefit of the provision of this habitability hardware.

Spacesuits are essential equipment for crewmembers living and working in the extreme environment of space. Achieving suit fit and comfort has been a challenge for designers. In a study that was conducted in January 2008, data were collected on three subjective measures of comfort in the advanced crew escape suit (ACES), the Mark III suit, and the rear entry ILC Dover suit (REI) (Harvey, Jones, Whitmore, & Gernhardt, 2008). With regard to overall discomfort, subjects documented that no matter which spacesuit they were in, they experienced some level of discomfort, and this level of discomfort increased during pressurized testing. Specific anatomical regions where discomfort was noted were the shoulders, back, neck, knees, and lower arms. Suit discomfort can reduce the safety and efficiency of all aspects of crew performance. These issues will become more important for long-duration planetary habitation due to the large number of anticipated EVAs that will be required. More suit-related information can be found in contributing factor 1 (Anthropometric and Biomechanical Limitation: Suit Effects).

Contributing Factor 7: Visibility/ Window Design & Placement

Visibility and window design and placement are contributing factors to the risk of incompatible vehicle/habitat design when the lighting system, windshield/window, glare, reflection, or other visual obstructions prevent necessary visibility and create an unsafe situation. Poor visibility conditions are a likely contributory cause for error, injury, or poor task performance. Critical visibility conditions, once identified through concept of operations development and task analyses, may be modeled with sufficient fidelity to assess the lighting and visibility necessary for task completion.

The likelihood of the occurrence of this contributing factor is directly related to humans' ability to accurately predict lighting conditions that provide the visibility necessary for task completion or our ability to maintain the required conditions throughout the mission. An inability to provide resupply light sources could result in poor visibility as has occurred on ISS. The provision of adequate lighting conditions is essential for any living and working environment, including onboard the ISS, to ensure proper visibility for task performance. Although the ISS has increased substantially in size, it still remains a confined environment for crewmembers to live and work. It limits crewmembers to only the lights provided in modules and additional lighting provided by portable and handheld lights. Several issues have arisen with lighting onboard the ISS (Baggerman et al., 2004). Lighting in some ISS modules was not originally installed in a manner that would provide the maximum amount of light output for lighting fixtures. In addition, lights have failed throughout the life of the ISS and limits on launch mass and volume have prevented the delivery of replacement light fixtures. Lighting in the ISS Node 1 module has been further affected by excessive stowage that has blocked operational lights, reducing the reflectivity of surrounding surfaces. Because of low lighting levels, some crewmembers have had to move certain tasks out of Node 1 to perform them, which increases the time necessary to perform tasks and decreases efficiency. Working behind panels or racks without dedicated lighting has been difficult for some crewmembers. This situation forces them to accommodate and make up for the poor design by using other types of portable lighting while searching for items or working behind panels. In summary, these impedances and inadequacies related to lighting have contributed to risks to efficiency onboard the ISS.

A key component to optimized visibility in the design of space vehicles and habitats is the provision of windows. Windows provide additional onboard lighting, crew earth observation capability, scientific observation and measurement capability, and rest, relaxation and improved crew morale. Space vehicle and habitat windows must allow for successful viewing and imaging. The number of windows provided, placement of windows and accessibility and restrictions on use of windows due to various constraints must be considered to optimize design and use. Effective window use first requires the determination of necessary viewing tasks and the hardware necessary to perform these tasks. This then allows for the proper determination of the size of a window port and its prerequisite optical properties. It must be considered that the provision of windows onboard space vehicles and within habitats is often limited and may require that a multitude of tasks be performed at a limited number of windows to achieve mission objectives.

According to the FCI ISS Crew Comments Database, previous crewmembers consistently emphasize not only the operational, but psychological importance of windows. Windows and the opportunity to look out available windows are an important component to sustain crews and maintain morale for long-duration missions. Restrictions on the use of existing onboard windows create some frustration among crewmembers and the provision of as many windows as possible is often emphasized. The addition of the Cupola viewing module, especially in its current position in Node 3, has increased the interest and importance of window observation and of course operations for ISS crews. The Cupola viewing module is predominantly used daily for tasks such as crew earth observation and photography for both pleasure and research. It is also used to provide out-the-window views for docking, EVA, and robotics operations. The Cupola contains a robotics workstation that allows 2 crewmembers to conduct robotics operations while viewing operations outside the ISS. Out-the-window viewing capabilities, especially those provided by windows in the Cupola, have been noted to be therapeutic and provide peace and serenity along with the operational benefits of window views (Figure 6). Windows are an essential part of vehicles and habitats for short and especially long-duration missions for both optimized task performance and crew morale and wellbeing.

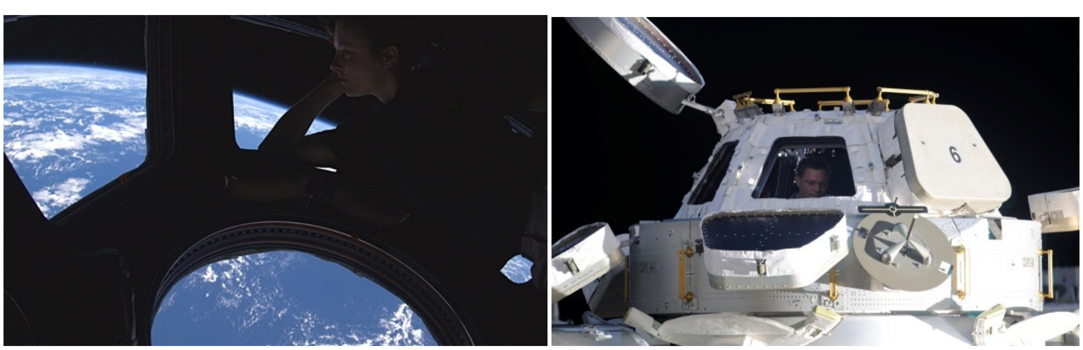

Figure 6: Out the window view at Cupola. (Photos courtesy NASA)

Contributing Factor 8: Vehicle/Habitat Volume/ Layout

Vehicle and habitat volume and layout are contributing factors to the risk of incompatible vehicle/habitat design when the design and layout prevents effective and efficient performance of crew tasks within and outside the vehicle and creates an unsafe situation. Habitats can influence the life and health of the crew, physiological and psychological design drivers, operational compatibility and manufacturability, and crew accommodations (Klaus & Higdon, 2009). Inefficiencies in spaceflight vehicle and habitat architectural design can affect crew safety, efficiency, and habitability. Specifically crew accommodations are essential mission elements like hardware and software that serve human needs (Stillwell, Boutros, Connolly, Woolford, & Bond, 1999). The habitat/vehicle should not be designed without consideration of the tools necessary and the tasks performed by the crew. Additional information on RSI and musculoskeletal injuries can be found in the general information of contributing factor 1 (Anthropometric and Biomechanical Limitations).

Crew accommodations vary based on many factors including mission operations, tasks and physical characteristic of humans. Therefore, appropriate habitat configuration and adequate provision of volume and square footage, whether inside or outside of the vehicle, is imperative to ensure compatibility with the characteristics and capabilities of the crew and the necessary tasks they will perform. Habitat configuration and volume can be impacted by specific task design or incompatible tasks that are required to be completed in a co-located area or by the actual physical characteristics of the crew. Insufficient net habitable volume and inappropriate functional arrangements can lead to impacts to productivity and habitability. Tasks that are unique for long duration missions must be considered in vehicle/habitat design. Currently crewmembers living onboard the ISS perform tasks including science and payload operations, maintenance of onboard equipment and systems, crew earth observation, robotics operations, extra vehicular activities, stowage and inventory management, and habitability related tasks including exercise, dining and hygiene. In regards to tasks expected of crewmembers for future long duration missions, there are several Design Reference Missions and related tasks under consideration. A detailed task analysis was performed to support the Orion program to determine required tasks for these missions (See Appendix A for a snapshot). While this task list will not be directly applicable due to program changes, it provides an illustration of typical tasks, which will likely occur. The Orion Master Task List identified and defined tasks for all phases of flight including launch, ascent, low earth orbit configuration, rendezvous proximity operations and docking, docked and departure, deorbit and landing operations, and recovery operations. Specific tasks within these mission phases include vehicle, system and equipment monitoring via displays and controls, suit and seat configuration, suit and vehicle leak checks, docking tasks such as hatch operations, stowage management, and habitability tasks.

Volume, Co-location and Topology

Functional volume, also referred to as net habitable volume (NHV), is the accessible volume available to crew in which they can perform required mission tasks. The use of a structured iterative design and evaluation process to define, calculate, and preserve functional volume helps to ensure that crew are provided adequate volume within which to perform these tasks and optimally function in their environment. There are several methods and processes used to drive designs and assess the functional volume of systems and vehicles. Although the specific methods may vary, proper assessment requires careful consideration of human operational needs during the mission. For example, considerations need to be made as to how crew will move or translate from task to task throughout the course of a mission, as well as how multiple crewmembers may perform simultaneous tasks. Functional volume design is thus a core component of a system's iterative human-centered design process. Additional information on how to ensure that the crew have enough room to safely and effectively perform mission tasks can be found in Section 8.2.4 of the HIDH, Internal Size and Shape of Spacecraft and Net Habitable Volume Verification Method (NASA, 2011a).

Mass and volume are highly constrained for spacecraft. The living accommodations must be as small as possible while still enabling the crew to accomplish its mission. The co-location of certain functional habitability areas has been problematic throughout long-duration spaceflight due to vehicle size and topology constraints. Lessons learned from data collected in the FCI ISS Crew Comments Database provide evidence that adjacency of sleeping quarters with the waste and hygiene facilities onboard the ISS has not proven optimal due to the noise made by the equipment, which can disrupt crew sleep. The co-location of dining facilities near exercise equipment and waste collection facilities compromises the scheduling of meals by influencing when food preparation and dining can be scheduled (Figure 7). Although it is possible to conduct dining activities while other crewmembers are exercising or using the waste collection system, it is not optimal. In addition, locating dining facilities near laboratory work jeopardizes both habitability and the integrity of science activities. The integrity of science can be compromised by the introduction of foreign debris (such as food products), which can alter the results of the experiment by contaminating an environment that should be controlled.

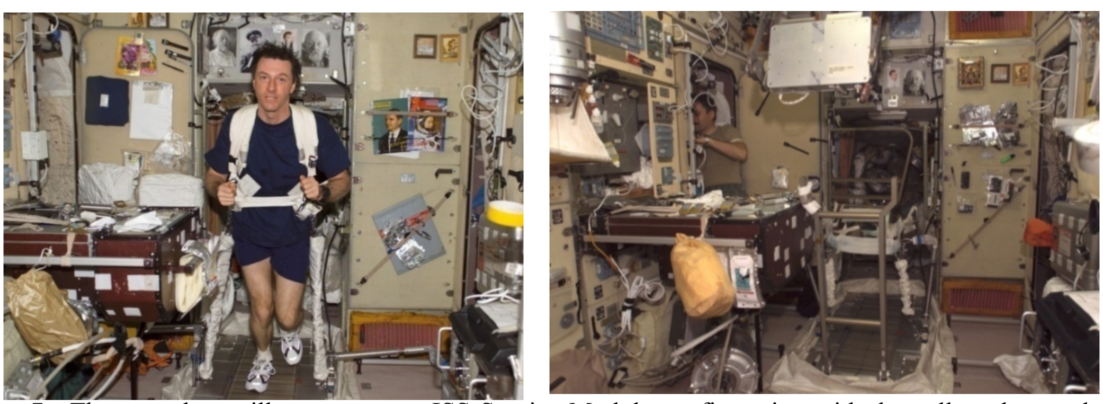

Figure 7: The two photos illustrate a poor ISS Service Module configuration with the galley, the treadmill, crew quarters, and waste and hygiene facilities co-located in the same habitable volume (Photos courtesy NASA).

Overall topology of spaceflight habitats has negatively affected ISS crew accessibility. For example, the U.S. cycle ergometer (CEVIS) blocks access to the US Laboratory module window. Physical and visual access to onboard windows has been very important to crewmembers for their mental health and overall judgment of habitability. Restricted access and blocked translation paths contribute negatively to the overall safety and efficiency of the crew, especially in the event of an emergency. More details on windows are discussed under contributing factor 7 (Visibility/ Window Design and Placement).

Accessibility

ISS accessibility problems are caused by obstructions and by the design and integration of hardware (Baggerman et al., 2004). The interior components of the US segment of the ISS are grouped into a series of "racks" which were designed to rotate, or tip over, to provide crew access to the rack utility connections and the module wall. However, crew feedback has indicated that rotating the racks is not an effective way to access utilities and connectors in a microgravity environment. The clearance required for human accessibility has been repeatedly cited as an issue in rack rotation capability. The design of the panels and drawers with these racks has compromised crew accessibility because many of them "stick" on-orbit due to the design not operating as intended in 0g, or too many items are placed in these stowage locations and not organized to afford easy operation. More details are discussed under contributing factor 1 (Anthropometric and Biomechanical Limitations).

Stowage

Stowage is a critical component of the usability and design of spaceflight vehicle and habitats. On-orbit stowage includes both the location of and the organization of stowed items. Operations are impeded if stowed items cannot be easily located or identified. With increased and accumulating stowage onboard the ISS, there has been a need to stow items in front of panels and in translation paths, resulting in the crewmembers' reduced ability to access items quickly. In addition, the crew must interface with a lot of cables throughout station that get added, routed and rerouted. Cable routing can block access to panels and stowage locations and can create operational constraints. Increased onboard stowage and the need for additional stowage management methods has led to the recent introduction and use of radio frequency identification (RFID) tags on board the space station to track stored objects. The effectiveness of this technology is currently being evaluated by the crew onboard the ISS.

The ISS onboard stowage accumulation has also been exacerbated by the buildup of packing materials that arrive with each shipment (by either space shuttle or resupply vehicle, such as the Russian Progress Module). Limitations associated with the ability to dispose of packing materials results in excessive amounts of stowage space used for waste. The amount of stowage on the ISS has increased to the point where all designated stowage areas are full and items are now being stowed in areas intended for habitability and work-related functions. Items are now stowed in passageways and in front of other stowage areas. In some instances the stowage violates the allowable limits requirements for the habitable volume areas. When crewmembers are searching for items, they must move many other stowed items out of the way to gain access to where a desired item is located. During some ISS expeditions, stowage has been located in the translation aisle and has blocked emergency fire ports. This specific issue serves as an example of the risk that excessive stowage can impose on the crew's safety.

Another important aspect of stowage management, to optimize vehicle design, configuration and habitability, is balancing the launching of ISS supplies (manifest). Crew also need the ability to dispose of waste and return items to Earth (down mass) in order to maintain habitable conditions on the ISS (Baggerman et al., 2004). ISS stowage previously impacted habitability due to an imbalance between the space shuttle launch and return mass limits, due to the grounding of the space shuttle after the Columbia accident and the lack of a systematic approach to dispose of unused hardware and supplies. Because the amount of onboard stowage has, at times, exceeded the allowable ISS requirements for acceptable levels of stowage in the habitable volume, stowage levels are constantly tracked and evaluated. Over a period of time, the onboard inventory of supplies (such as clothing and hygiene supplies) has increased and still the manifesting of these supplies continues. Each ISS expedition crewmember brings a selection of personal items with them to the ISS and at the end of their stay, the unused items remain. This increase in inventory contributes to crew safety risks, as ample stowage space is not available to accommodate placement of items outside of the habitable volume and translation paths. This situation has improved somewhat as the inventory management function has improved and the manifesting process has been streamlined, yet it continues to be a problem due to the lack of, and inconsistent nature of disposal capability through space shuttle flights and inconsistent practices for tracking hardware and supplies.

Habitat Configuration (for EVA Operations)

Habitat configuration should not only be addressed for internal volume spaceflight activities, but also internal EVA spaceflight activities. Internal EVAs occur when a module of the spacecraft becomes depressurized and crew is required to access and repair the module while suited. Habitat configuration also is a key component for task efficiency during maintenance and repair operations during EVAs where safety may be especially vulnerable. Off-nominal maintenance onboard the Mir space station provided some insight into safety risks related to on-orbit operations and habitat configuration. When a Russian Progress module collided with Mir, the Spektr solar array and thermal control system radiator were damaged, which led to the depressurization of the Spektr module. Repairing the module and its components required the crew to perform an internal EVA and enter the depressurized module wearing space suits. Once the Mir hatch was closed, the crew reconnected the electrical power lines. Detailed safety and operations assessments were conducted including assessment of the environment of the Spektr module. Consideration had to be made for the fact that the hardware and experiments had now been exposed to space and there would be limited area within the habitable volume for the suited EVA crew to move and work inside the module. Potential hazards included sharp edges, fragile materials, fluid contamination, touch temperature issues, and entanglement hazards from fans. An internal EVA hazard assessment was conducted based on the identification of these hazards to determine worst case risks for each hazard, determine methods for mitigation and control and develop procedures and training to ensure the crew could safely conduct the operations. In the end, the internal EVA was completed successfully without encountering any hazards. Although the configuration of this particular work environment was extremely unique, it is still important to consider potential issues with habitat configuration in these types of off-nominal situations to ensure crew safety and efficient task performance is maintained.

Another aspect of spacecraft habitat design, volume and internal configuration is the consideration of translation hatch size and shape. Hatch design concepts for the planned Altair lunar habitat were assessed by Thompson et al. (2008), in an attempt to understand crew performance while translating through the Altair hatches. Contrary from the Apollo lunar module, the Altair Lander will be larger and sustain four crewmembers on the surface of the Moon for a week. The vehicle design includes three hatches used for docking, internal transfer, separation between the habitat and airlock and access to the lunar surface. The evaluation included an assessment of rectangular and circular shaped hatches that varied in size by height, width and step-over height, in an attempt to evaluate critical dimensions for hatch translation. A pressurized rear-entry integrated (REI) EVA suit was worn for all test configurations and a portable life support system (PLSS) was attached to the suit during testing. The participant chose their own method for translating through the hatch. Objective data collected included time and contact data with the hatch. The greatest frequency of collisions occurred to the upper portion of the hatch, which was attributed to the PLSS. Subjective data were also collected. The data collected revealed a significant relationship between the height of the hatch and all of the performance measures, along with step over and overall height and some of the dependent scores. Based on these findings, the researchers recommended considering the interaction of hatch height and step-over height, allowance for standing postures, collisions with the hatch and potential safety issues related to damaging suits. All of these considerations emphasize the importance of appropriate volume within spacecraft to allow for translation, efficiency and safety.

Exterior design of the spacecraft also affects the translation, efficiency and safety of external EVA spaceflight activities. Hatch opening, ingressing the hatch, handrail removal, closing the hatch, and handrail translation tasks were examined in a joint Constellation Program (CxP)/International Space Station (ISS) integrated test conducted with participation from the Extravehicular Activity Systems Project Office (ESPO) and the Orion Project Office (DeSantis et al., 2011). The test conducted by DeSantis et al. (2011) took place in the Neutral Buoyancy Laboratory (NBL) with subjects wearing Extravehicular Mobility Unit (EMU) suits. Ratings were provided by the subject using a usability ratings scale, Cooper-Harper Scale (for overall handling qualities of the suit) and the Maneuverability Assessment Scale for three scenarios: 1) ISS-based EMU EVA (i.e., translation began at ISS node handrail to the Orion side hatch), 2) Altair-to-Orion Transfer (i.e., translation began at Altair handrail to the Orion side hatch), and 3) Orion-based EVA (i.e., translation began from inside the Orion side hatch to remove EVA handrails) Locations for needed handrails were identified and for some hatch activities, the lack of a defined handhold affected participants' ability to close a hatch. For example, when observed, all subjects in the ISS-Based EMU EVA were observed egressing the hatch almost out to their waist in order to grab onto an indentation in the hatch in order to close it. Within this same scenario, one subject (with the shortest arm span) was unable to complete translation, hatch opening, or hatch closure tasks. It was suggested that EMU suit architecture limitations could have adversely affected smaller participants. Hatch ingress and hatch closure activities involved inadvertent contact with hatch seals. So habitat components (e.g. hatches, handrails, and translation paths) needs to consider both the human limitations (e.g. suited small arm span) as well as components that could be affected by potentially repeated contact (e.g. hatch seals).

Computer-Based Modeling and Simulation

Understanding and predicting human-system performance and identifying risks that may be inherent in a concept or a design is often achieved via computer-based modeling or simulation. The use of human performance models when used in concert with human-in-the-loop evaluations can be quite effective and cost efficient in habitat design, but accurately modeling the human is extremely difficult. We do not have high-fidelity human performance models, and most of the existing models have not been sufficiently validated or certified. This is exacerbated when pressure garments as bulky as EVA suits are considered.

NASA has performed a wide variety of human factors-related modeling and simulation (M&S) work, including human anthropometric modeling, habitat volumetric analysis and layout design, spacecraft interior lighting and acoustic modeling, and human task performance modeling. This section provides some examples of the modeling work completed at NASA, and outlines some potential M&S challenges (and thus research gaps) relevant to Space Human Factors Engineering (SHFE). The section focuses on two areas: Modeling and simulation of the human, vehicle/ habitat and environment, and human task performance modeling.

Modeling and Simulation of the Human and Vehicle/Habitat

This section describes examples of anthropometric and human modeling, as well as environment modeling and simulation at NASA, including implications for habitat design.

Anthro-Plus Project – The purpose of the Anthro-Plus project (Thaxton, England, Tran, & Wheaton, 2008) was to advance understanding in the state-of-the-art capabilities and applications of physical human modeling technologies to aid physical environment design. The project consisted of three key efforts: (1) a survey of software vendors to evaluate modeling capabilities, (2) a survey of software users to review the application of models in industry, and (3) a laboratory evaluation of human modeling software-acquired predictions for a specific task. In addition, a library of portable static mannequins was developed and dialogue was opened with potential stakeholders to assess specific modeling needs and requirements.

The vendor and user survey concluded that three modeling software packages considered to be the most capable of serving NASA needs in the near future were: Jack, RAMSIS, and Safework. Software users in a variety of industries used human modeling software for varying purposes, but a common theme was for the physical M&S-based analysis to be completed in the early design phases, when there was still an option to change the design of the habitat/workplace, rather than in the requirements verification phase where actual physical changes to habitats may not be easily correctable. Human modeling is helpful to identify injury risk, timing, user comfort, reach/accessibility, as well as other human factors parameters. When habitat dimensions are known, the placement of accurate human models (as represented by the static mannequins) can also illustrate where some operational concepts might fail. For example, when designing crew quarters layouts, through M&S, designers may ask: "Can the crewmember fit into the space without contortions?" and "What is the optimal placement of other crew quarters components (e.g. Communication panels and, Caution and Warning displays)?" Human factors experts were almost always the direct users of physical human modeling software for providing input to equipment or task designers.

The laboratory evaluation of human modeling software by Thaxton, et al. (2008) compared the anthropometric data of six subjects acquired from a 3D laser scanner to Jack mannequins. Subjects and the Jack mannequin were both reaching for targets. The results for each posture, indicated in pass/fail measurements, ranged from 50% to 100% in accuracy with an average of 78%. Jack predicted less reach capability than demonstrated by the subjects. Accuracy of predictions for each test subject over all postures combined, compared to Jack, ranged from 75% to 100% with average of 93%. Differences in model results imply that models were not depicting human posture accurately. Discrepancies are expected, but they strongly affect model predictions for tasks such as the one used in this study.

For the last *Anthro-Plus* effort, an electronic library of static mannequins was developed based on HSIR critical dimensions (see Appendix B for a sample). This project provided a greater understanding of the capabilities and applications of human modeling software, and gave insight into the practical considerations and accuracy of human models. The outcome was provided to the SHFE community supporting the Orion Project to explore the feasibility of using accurate simulation-based acquisition processes for habitat layout design. It was concluded that there was a need for further refinement of models for a more realistic representation of posture/movement, as well as microgravity data for accurate model development/customization and validation.

3D Human Physical M&S for Ground Operations – In the early stages of the Constellation Program, 1-G human factors requirements were not well defined, in particular for Ground Support Systems (GSS) and Ground Support Equipment (GSE). Stambolian (2009) documented the steps taken to infuse human factors requirements and processes in a project that used human motion capture and 3D human physical M&S to optimize the ground operation assembly process for the CxP Ares-I vehicle. The goal of this work was to demonstrate that the techniques for assembling the Orion spacecraft are devised, not by trial-and-error inside a multi-million-dollar capsule, but by computer in a virtual world where "no one can drop a life support system on their toe or wrench their back while moving equipment inside." This work obtained its goal by demonstrating effective human factors involvement in the review and evaluation of 30% and 60% design packages and has expanded the evaluation process into a tool that can be used by the designers to ensure they are using the appropriate MIL-STD-1472 standards.

Modeling and Simulation of the Environment

Environment modeling (e.g., acoustics, lighting, vibrations) efforts to date at NASA have mostly included lighting and acoustics. These models and simulations were primarily used for assessing habitat designs and compliance with the related human factors requirements.

Spacecraft Interior Lighting Prediction – Maida (2007) used computer-generated illumination maps to predict interior lighting conditions on the International Space Station (ISS). After the STS-115 Columbia accident in 2003, re-supply missions to the ISS were greatly reduced. Meanwhile, many of the lighting systems began to reach their end of life, and replacements were not keeping pace with failures. As there were no onboard measurements of illumination, there was no clear understanding of the lighting conditions on ISS, other than the subjective assessments of the crews. To provide an objective estimate of conditions, the Radiance lighting modeling system, adapted and validated by the Graphics Research Analysis Facility (GRAF) at the Johnson Space Center for use in space human factors analyses, was used as a virtual light meter to predict the illumination levels onboard ISS so that they could be compared against ISS program requirements. The number and location of functioning and failed lighting systems was tracked over time and modeled accordingly. At each stage of a failure or replacement, the modeling system computed the illumination within the U.S. Laboratory, Node 1, and airlock modules, and compared those results with the ISS program requirements for a variety of tasks and conditions. These results provided the ISS program managers and safety engineers a better understanding of the conditions onboard the ISS to help set priorities for supplying spare lighting systems. While this is one example of the value of modeling habitat lighting in established systems, lighting M&S could also help shape the requirements for future vehicle and habitat designs.

Spacecraft Interior Acoustic Modeling – Concerns regarding acoustic levels in habitats is not limited to the protection of crewmember hearing. Critical tasks with audible alarms, and crew-crew and crew-ground communication can be negatively impacted by high noise levels. Misunderstandings in communication can lead to human errors. Therefore, when acoustical modeling can be applied, it is of great benefit to crew health and performance. Chu and Allen (2011) led a project that modeled the interior acoustic levels of both the ISS and the Orion Crew Module (CM) spacecraft. This project demonstrated the benefits of using acoustic mockups with incrementally increasing fidelity to develop and validate spacecraft cabin acoustic models. The results from this investigation were provided to the Orion Project, and supported the development of system level noise treatments for the Orion vehicle.

Future research/development work includes:
- Validation of structure-borne noise in acoustic models
- Validation of low-frequency acoustic models including resonant modes in ducts and ventilation systems
- Inclusion of suited crewmember in acoustic models

Human Task Performance Modeling and Simulation

Modeling of human performance behaviors is as critical as modeling of anthropometric characteristics and environmental factors in habitat design; this is particularly true for long-duration spaceflights. The following examples describe promising initial steps towards effective use of cognitive and human performance modeling and simulation in habitat design and evaluation.

MIDAS Human Performance Model Development – Gore (2011) developed a human performance model called Man-Machine Integration Design and Analysis System (MIDAS), which has been used in various human performance projects since 1986. Human Performance Models (HPMs) can be used to study the impact of assistive technologies on the human operator in a safe and unobtrusive manner. MIDAS is a dynamic, integrated HPM environment that facilitates the design, visualization, and computational evaluation of complex human- system concepts in simulated operational environments. MIDAS symbolically represents many mechanisms that underlie and cause human behavior. It combines graphical equipment prototyping, dynamic simulation, and HPMs to reduce design cycle time, support quantitative predictions of human-system effectiveness, and improve the design of crew stations and their associated operating procedures. The current MIDAS v5 architecture includes three major Modules: Inputs, Processing, and Output. The Input Module includes the operational environment, the operator tasks, and operator process models. The Processing Module is composed of a task manager model that schedules tasks to be completed. It also contains the model state definitions within the physical simulation and a library of basic human primitive models that represent behaviors required for all activities. The "cognitive" component of the Processing Module is composed of a perceptual mechanism, memory, a decision maker, and a response selection architectural component. Lastly, the Output Module generates a runtime display of the task network, the anthropometry, as well as mission performance. MIDAS has been successfully applied and validated in two aviation projects: 1) Human error model of an aviation surface-related application, and 2) Approach-and-land operations (Gore, 2011).

Significant challenges still exist for MIDAS and state-of-the-art in HPMs in general, in terms of model transparency and validation, and for space applications. "Transparency" refers to the ability to comprehend model performance, the relationships that exist among the models being used, and whether the model is behaving as expected. Validation remains a large challenge for the HPM community because statistical validation is often seen as the Holy Grail for determining model suitability.

Orion Human Performance Model Development – Wong, Walthers, and Fairy (2010) developed a Discrete Event Simulation (DES) model to look at workload during activities associated with Orion's Rendezvous, Proximity Operations, and Docking (RPOD) to the ISS. A DES is a computer model that dynamically simulates the work performance of human operators. The authors also developed an associated validation strategy for potential use of the model in human error analysis.

The RPOD model consists of two major components: a Master Task List (MTL) as its input, and the human performance DES model itself. Both the MTL and human performance DES models were developed based on continual inputs from Subject Matter Experts (SMEs), archival data, space flight documentation, training materials, human performance research literature, and standards such as NASA-STD-3001 (NASA, 2011b).The human performance model component was constructed using the Improved Performance Research Integration Tool (IMPRINT Pro v.3.0), which is a dynamic, stochastic, discrete event modeling tool designed and maintained by the U.S. Army Research Laboratory. The DES model was validated using a combination of methods:

1. The development of the model was carried out early in Orion's design.
2. The development adhered to NASA's modeling and simulation development standards (NASA, 2008).
3. Stakeholders, NASA astronauts, SMEs, and NASA's modeling and simulation development community was involved in the development.
4. Standard and repeatable validation methods (i.e., face, content and output validity) were applied to ensure the model's accuracy (DMSO, 2006; NASA, 2008).
5. Lastly, the data from a separate HITL RPOD simulation was used to provide an additional means of estimating the model's validity.

This validation strategy appeared to show promising results. Due to the preliminary nature of this work, however, the results cannot be generalized without data to validate the method.

Research & Implementation Challenges of Human Modeling & Simulation

Despite the wide portfolio of M&S-related work, work is still needed to address proper model usage, improve fidelity, and enhance validation methodologies. Literature we have collected on general human M&S suggests that the use of human M&S can result in significant lifecycle cost savings (Young, 1997) and (Booher, 1997). For example, the use of human modeling tools in the development of the Comanche attack helicopter resulted in a savings-to-investment ratio of 44:1 (Booher, 1997).

One of the M&S issues is that although numerous efforts have focused on developing human models, especially human physical models ranging from low to high-fidelity (Wakeling & Lee, 2011, June 5 - 8) and (Tibold, Fazekas, & Laczko, 2011), most of these efforts have focused on limited aspects of the human (e.g., only the purely anthropometric aspect or the cognitive aspect); accurately modeling the human as an entire system has yet to be realized (Alexander & Conradi, 2011). Another issue has to do with model development and the Validation & Verification (V&V) process. Some researchers Banks and Chwif (2010), Gore (2011), and McCann and McCandless (2002) suggest that an appropriate approach to human M&S should involve properly applying both M&S and HITL evaluations. This approach has the advantages of allowing incremental model development through iteratively refining model fidelity, and facilitating model V&V through the availability of data from HITL evaluations. Lucas and McGunnigle (2003) also propose that a combination of multiple simple models can sometimes yield better results than a single highly complex model when the combined simple models strike a good balance between cost, effectiveness, and realism. However, as suggested by Gore (2011), transparency of the models then becomes more of an issue as the number of models increase. Additional tools may be needed to help keep track of and document these models.

Another important issue is how to verify/certify existing models. NASA-STD-7009 (NASA, 2008) contains high-level requirements for carrying out model verification/accreditation (certification) in general. High-level requirements for verification are:

Req. 4.4.1 – Shall document any verification techniques used and any domain of verification (e.g., the conditions under which verification was conducted).

Req. 4.4.2 – Shall document any numerical error estimates (e.g., numerical approximations, insufficient discretization) for the results of the computational model.

Req. 4.4.3 – Shall document the verification status of (conceptual, mathematical and computational) models.

High-level requirements for validation are:

Req. 4.4.4 – Shall document any techniques used to validate the M&S for its intended use, including the experimental design and analysis, and the domain of validation.

Req. 4.4.5 – Shall document any validation metrics, referents, and data sets used for model validation.

Req. 4.4.6 – Shall document any studies conducted and results of model validation.

As model verification/certification is a major part of any system's development, methodologies to certify complex models with large number of state parameters become critically important (Wong, 2012).

For space habitat design, the Space Human Factors Engineering (SHFE) domain faces challenges similar to the general M&S community, but with the added complexity and uniqueness of the microgravity environment. Additional research is needed to develop high-fidelity human models for the microgravity environment. Since operational on-orbit data is crucial for accurately modeling/simulating the crewmember in space, there is a need to establish practical mechanisms to collect, compile, analyze, and disseminate microgravity data to support development and validation of models.

In summary, below is a list of the major M&S challenges that SHFE is currently facing:

- How do we ensure models are correctly used?
- How can we appropriately increase the fidelity of models?
- What steps should be taken to achieve an accurate human model?
- How should M&S and human-in-the-loop evaluations be properly applied during design?
- How do we properly document models to ensure transparency?
- What general tools can we adopt/develop to enhance the effectiveness of the M&S process?
- How do we certify highly complex models?
- How do we develop high-fidelity human models for the microgravity environment?

The list above is no doubt only a partial list of all of the human M&S challenges. However, a comprehensive literature review is planned to identify additional current state-of-the-art M&S technologies, and current research development efforts and challenges.

Risk in Context of Exploration Mission Operational Scenarios

Future exploration missions will increase in length, thus requiring newer technologies and an increase in autonomy. Lunar missions will provide a substantial set of independent lessons learned, experiences, and more definitive knowledge gaps that will apply to Mars exploration. Crews will face the challenges of prolonged isolation and confinement, significant communication latencies, environmental stressors, and increased responsibility and autonomy. Effective design solutions for vehicles, habitats, and missions need to allow the management and control of all aspects of exploration mission operational scenarios.

Human factors principles must be implemented in all aspects of the design process to mitigate or prevent the space human factors engineering risks from occurring. Designing for reduced gravity will be critical. Lunar and Martian environmental conditions – air quality, lunar or Mars dust, radiation exposure, and lighting – must be addressed. Stowage provisions need to ensure that appropriate spares and stowage volumes are available and accessible in a timely manner. Intuitive human-computer interaction will be necessary with increasingly complex task demands and autonomy. The reduction in required maintenance and interface with complex systems should be implemented. To avoid the risk of incompatible spaceflight vehicle and habitat design and ensure optimized operational mission scenarios, considerations must be made for anthropometric and biomechanical limitations, motor skill/coordination or timing, space and lunar visual environments, vibration and g-Forces, noise interference, seating, restraints and equipment, window design and placement and vehicle/habitat volume/layout.

Gaps

Evidence supports the claim that poor vehicle/habitat design leads to inefficiencies and potential safety concerns. Therefore, it is critical that all the contributing factors are well-understood and considered effectively in vehicle/habitat design. Potential gaps related to incompatible vehicle and habitat design may relate to design guidance, methods, and metrics needed to ensure future successful missions. The gaps include, but are not limited to:

- Guidelines to select, assess, create and use proper user population databases
- Practical, efficient and effective methodologies for ergonomic (including anthropometry, biomechanics) evaluations to demonstrate vehicle accommodation of crew capabilities and limitations
- More accurate human models for digital modeling analysis with the right level of fidelity/accuracy
    - Onboard (microgravity) operational performance data for model development and validation

- Methodologies and metrics for integrated vehicle/system level evaluations leveraging multiple, complementary tools/methods such as digital modeling, HITL evaluations, and population analysis
    - Methodologies for assessing/validating vehicle layout/volume effectiveness for specific mission objectives/scenarios (in particular reliable metrics/methodologies to demonstrate return on investment)
    - Spacecraft/ integrated system level habitability assessment methodologies and metrics such as Post Occupancy Evaluations (POE), habitability assessment as well as sub-system and component level usability to validate the design requirements and capture lessons learned systematically during the operational phase
- Guidance regarding what needs to be done when we don't have appropriate (proper fidelity) prototypes and mock-ups, such as suits for HITL evaluations
- Critical factors/considerations for vehicle/spacecraft design (layout, volume, and configuration)
- Innovative stowage packaging, and effective space utilization
- Effective stowage utilization/tracking aids

A description of all SHFE gaps can be found in the Human Research Roadmap Content Management System at http://sa.jsc.nasa.gov/hrrcms/.

Conclusion

The risk of poor vehicle/habitat design relates to vehicle, habitat and workstation design and how they accommodate the wide range of human physical characteristics, capabilities and limitations, given that the duration of crew habitation in these space-based environments will be far greater in the future than missions of the past. The critical contributing factors to this risk are: anthropometric and biomechanical limitations, motor skill/coordination or timing, space and lunar visual environments, vibration and g-forces, noise interference, seating, restraints and personal equipment, visibility/window design & placement, and vehicle/habitat volume/layout. If not addressed properly, there is a potential of in-flight and ground crew performance degradation and errors, possible crew injuries, acute and chronic ergonomic-related disorders, and failed mission and program objectives.

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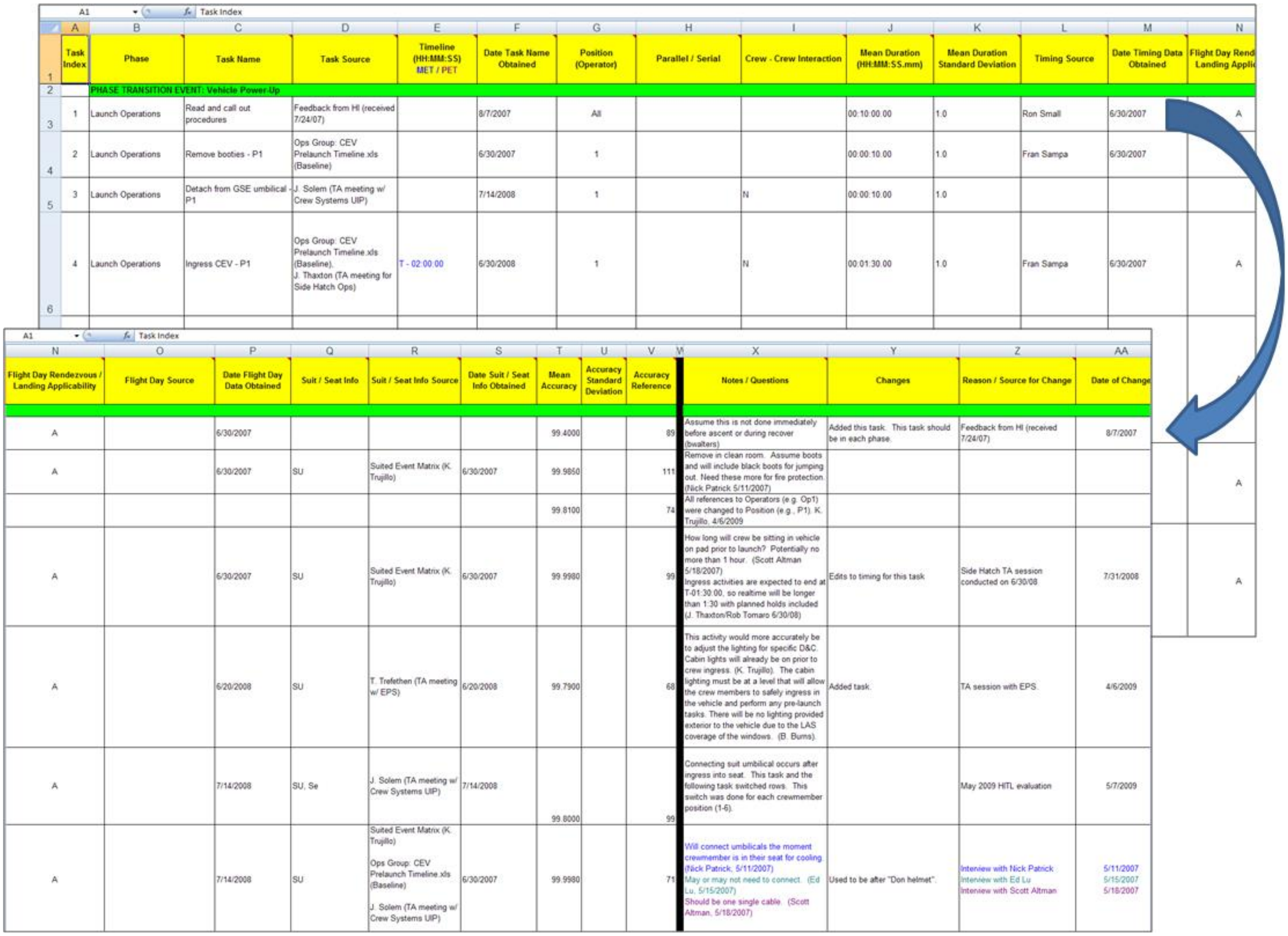
Team

Chris Blackledge, Ph.D.	MEI Technologies, NASA Johnson Space Center
Esau Perez, M.S.	Lockheed Martin, NASA Johnson Space Center
Sudhakar Rajulu, Ph.D.	NASA Johnson Space Center
Jim Maida	NASA Johnson Space Center

List of Acronyms

ACES – Advanced Crew Escape Suit
ANSUR – US Army Anthropometry Survey
CAESAR – Civilian American and European Surface Anthropometry Resource
CEVIS – US Cycle Ergometer
CHSIP – Commercial Human Systems Integration Process
CIAS – Crew Impact Attenuating System
C&W – Caution & Warning
CxP – Constellation Program
dBA – Decibel A-Weighting
DDT&E – Design, development, test and evaluation
EMG – Electromyogram
EMU – Extravehicular Mobility Suit
EVA – Extravehicular Activity
FCI – Flight Crew Integration
G – Gravitational acceleration
HFACS – Human Factors Analysis and Classification System
HIDH – Human Integration Design Handbook
HITL – Human in the Loop
HSIR – Human Systems Integration Requirements
HUT – Hard upper torso
Hz – Hertz
ISS – International Space Station
MPCV – Multipurpose Crew Exploration Vehicle
NASA – National Aeronautics and Space Administration
NHANES – National Health and Nutrition Examination Survey
NHV – Net Habitable Volume
OBSS – Orbiter Boom Sensor System
PLSS – Portable Life Support System
POE – Post Occupancy Evaluations
QD – Quick disconnect
REI – Rear Entry Integrated
SRMS – Shuttle Remote Manipulator System
STS – Shuttle Transportation System
TMG – Thermal Micrometeoroid Garment
US – United States
WinSCAT - Spaceflight Cognitive Assessment Tool for Windows

APPENDIX A: Snapshot of Orion Master Task List



Task Index	Phase	Task Name	Task Source	Timeline (HH:MM:SS) MET / PET	Date Task Name Obtained	Position (Operator)	Parallel / Serial	Crew - Crew Interaction	Mean Duration (HH:MM:SS.mm)	Mean Duration Standard Deviation	Timing Source	Date Timing Data Obtained	Flight Day Rend… Landing Applic…
	PHASE TRANSITION EVENT: Vehicle Power-Up												
1	Launch Operations	Read and call out procedures	Feedback from HI (received 7/24/07)		8/7/2007	All			00:10:00.00	1.0	Ron Small	6/30/2007	A
2	Launch Operations	Remove booties - P1	Ops Group: CEV Prelaunch Timeline.xls (Baseline)		6/30/2007	1			00:00:10.00	1.0	Fran Sampa	6/30/2007	
3	Launch Operations	Detach from GSE umbilical - P1	J. Solem (TA meeting w/ Crew Systems UIP)		7/14/2008	1		N	00:00:10.00	1.0			
4	Launch Operations	Ingress CEV - P1	Ops Group: CEV Prelaunch Timeline.xls (Baseline), J. Thaxton (TA meeting for Side Hatch Ops)	T - 02:00:00	6/30/2008	1		N	00:01:30.00	1.0	Fran Sampa	6/30/2007	A

Flight Day Rendezvous / Landing Applicability	Flight Day Source	Date Flight Day Data Obtained	Suit / Seat Info	Suit / Seat Info Source	Date Suit / Seat Info Obtained	Mean Accuracy	Accuracy Standard Deviation	Accuracy Reference	Notes / Questions	Changes	Reason / Source for Change	Date of Change
A		6/30/2007				99.4000		89	Assume this is not done immediately before ascent or during recover (bwalters)	Added this task. This task should be in each phase.	Feedback from HI (received 7/24/07)	8/7/2007
A		6/30/2007	SU	Suited Event Matrix (K. Trujillo)	6/30/2007	99.9850		111	Remove in clean room. Assume boots and will include black boots for jumping out. Need these more for fire protection. (Nick Patrick 5/11/2007)			
						99.8100		74	All references to Operators (e.g. Op1) were changed to Position (e.g., P1). K. Trujillo, 4/6/2009			
A		6/30/2007	SU	Suited Event Matrix (K. Trujillo)	6/30/2007	99.9980		99	How long will crew be sitting in vehicle on pad prior to launch? Potentially no more than 1 hour. (Scott Altman 5/18/2007) Ingress activities are expected to end at T-01:30:00, so realtime will be longer than 1:30 with planned holds included (J. Thaxton/Rob Tomaro 6/30/08)	Edits to timing for this task	Side Hatch TA session conducted on 6/30/08	7/31/2008
A		6/20/2008	SU	T. Trefethen (TA meeting w/ EPS)	6/20/2008	99.7900		68	This activity would more accurately be to adjust the lighting for specific D&C. Cabin lights will already be on prior to crew ingress. (K. Trujillo). The cabin lighting must be at a level that will allow the crew members to safely ingress in the vehicle and perform any pre-launch tasks. There will be no lighting provided exterior to the vehicle due to the LAS coverage of the windows. (B. Burns).	Added task.	TA session with EPS.	4/6/2009
A		7/14/2008	SU, Se	J. Solem (TA meeting w/ Crew Systems UIP)	7/14/2008	99.8000		99	Connecting suit umbilical occurs after ingress into seat. This task and the following task switched rows. This switch was done for each crewmember position (1-6).		May 2009 HITL evaluation	5/7/2009
A		7/14/2008	SU	Suited Event Matrix (K. Trujillo) Ops Group: CEV Prelaunch Timeline.xls (Baseline) J. Solem (TA meeting w/ Crew Systems UIP)	6/30/2007	99.9980		71	Will connect umbilicals the moment crewmember is in their seat for cooling. (Nick Patrick, 5/11/2007) May or may not need to connect. (Ed Lu, 5/15/2007) Should be one single cable. (Scott Altman, 5/18/2007)	Used to be after "Don helmet".	Interview with Nick Patrick Interview with Ed Lu Interview with Scott Altman	5/11/2007 5/15/2007 5/18/2007

APPENDIX B: HSIR Critical Dimensions

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TABLE B1-2 - VEHICLE DESIGN CRITICAL ANTHROPOMETRY DIMENSIONS

Design Concern	Critical Dimension	Numerical Code from Table B1-1	Minimal Clothing		With ACES-Type Suit, Unpressurized		With ACES-Type Suit, Pressurized	
			Min (cm [in])	Max (cm [in])	Min (cm [in])	Max (cm [in])	Min (cm [in])	Max (cm [in])
Maximum vertical clearance	Stature, standing	805	148.6 (58.5)	194.6 (76.6)	157.7 (62.1)	203.7 (80.2)	158.0 (62.2)	200.2 (78.8)
Vertical seating clearance	Sitting height	758	77.7 (30.6)	101.3 (39.9)	83.6 (32.9)	112.8 (44.4)	85.9 (33.8)	110.7 (43.6)
Vertical seating clearance with bailer bar down or removed	Sitting height without bailer bar**	758	NA	NA	82.3 (32.4)	105.9 (41.7)	NA	NA
Placement of panels to be within line-of-sight	Eye height, sitting	330	66.5 (26.2)	88.9 (35.0)	61.2 (24.1)	87.6 (34.5)	56.9 (22.4)	84.8 (33.4)
Top of seatback	Acromial height, sitting	N/A	49.5 (19.5)	68.1 (26.8)	48.8 (19.2)	68.8 (27.1)	48.3(19.0)	68.3 (26.9)
Placement of objects that may be over lap (panels, control wheel, etc.)	Thigh clearance, sitting	856	13.0 (5.1)	20.1 (7.9)	15.0 (5.9)	19.8 (7.8)	17.5 (6.9)	21.6(8.5)
Height of panels in front of subject	Knee height, sitting	529	45.5 (17.9)	63.5 (25.0)	47.2 (18.6)	66.3 (26.1)	51.3 (20.2)	69.9 (27.5)
Height of seat pan	Popliteal height, sitting	678	33.0 (13.0)	50.0 (19.7)	31.8 (12.5)	51.1 (20.1)	32.0 (12.6)	49.0 (19.3)
Downward reach of subject	Wrist height, sitting (with arm to the side)	N/A	39.6 (15.6)	54.6 (21.5)	41.1 (16.2)	62.5 (24.6)	45.0 (17.7)	63.5 (25.0)
Placement of restraint straps	Biacromial breadth	103	32.3 (12.7)	44.5 (17.5)	36.1 (14.2)	45.5 (17.9)	34.8 (13.7)	47.8 (18.8)
Width of seatback	Bideltoid breadth	122	37.8 (14.9)	56.1 (22.1)	53.1 (20.9)	66.3 (26.1)	58.4 (23.0)	70.9 (27.9)
Width of seatback for conformal seat	Bideltoid breadth in conformal seat**	122	NA	NA	41.8 (16.5)	60.1 (23.7)	NA	NA
Side clearance envelope, possible seatback width	Forearm-forearm breadth	378	38.9 (15.3)	66.0 (26.0)	69.3 (27.3)	87.6 (34.5)	82.3 (32.4)	100.6 (39.6)
Side clearance envelope, possible seatback width for conformal seat	Forearm-forearm breadth in conformal seat**	378	NA	NA	48.9 (19.3)	76.0 (29.9)	NA	NA
Width of seat pan	Hip breadth, sitting	459*	31.5 (12.4)	46.5 (18.3)	36.3 (14.3)	54.4 (21.4)	38.9 (15.3)	55.6 (21.9)

TABLE B1-3 - VEHICLE DESIGN CRITICAL ANTHROPOMETRY DIMENSIONS (CONCLUDED)

Design Concern	Critical Dimension	Numerical Code from Table B1-1	Minimal Clothing		With ACES-Type Suit, Unpressurized		With ACES-Type Suit, Pressurized	
			Min (cm [in])	Max (cm [in])	Min (cm [in])	Max (cm [in])	Min (cm [in])	Max (cm [in])
Width of seat pan for conformal seat	Hip breadth, sitting in conformal seat**	459*	NA	NA	32.8 (12.9)	48.8 (19.2)	NA	NA
Length of seat pan	Buttock-popliteal length, sitting	200	42.2 (16.6)	57.2 (22.5)	47.2 (18.6)	62.2 (24.5)	50.0 (19.7)	68.6 (27.0)
Placement of panels in front of subject	Buttock-knee length, sitting	194	52.1 (20.5)	69.9 (27.5)	59.9 (23.6)	73.9 (29.1)	66.3 (26.1)	82.0 (32.3)
Rudder pedal design, foot clearance	Foot length, sitting	362	21.6 (8.5)	30.5 (12.0)	27.2 (10.7)	38.6 (15.2)	27.2 (10.7)	38.6 (15.2)
Placement of control panels, maximum reach	Thumb tip reach, sitting	67	65.0 (25.6)	90.9 (35.8)	67.3 (26.5)	103.1 (40.6)	52.8 (20.8)	100.6 (39.6)

* For seated measurements, the largest female hip breadth is larger than the largest male hip breadth, and the smallest male hip breadth is smaller than the smallest female hip breadth; therefore, male data are used for the Min dimension, and female data are used for the Max dimension.

** Additional measurements are provided for specific hardware assumptions. These measurements were taken with a bailer bar either in a down position or removed, in a conformal-style seat that includes features such as a reduced angle between the hip and torso as well as shoulder bolsters. Measurements were taken only in the unpressurized suit condition. Because measurements for these hardware configurations are not provided for unsuited or pressurized suited conditions, the standard hardware configuration measurement should always be used for those suit conditions. More details pertaining to measurement assumptions may be found in Memo ZF-08-004: Application of HS2002 Anthropometric Critical Dimensions and Table B1-7 to Occupant Protection and Landing Strategy Tiger Teams.

TABLE B1-4 - SUIT DESIGN CRITICAL ANTHROPOMETRY DIMENSIONS

Design Concern	Critical Dimension	Numerical Code from Table B1-1	Minimal Clothing	
			Min (cm [in])	Max (cm [in])
Maximum vertical clearance	Stature, standing	805	148.6 (58.5)	194.6 (76.6)
Placement of headrest	Vertical trunk diameter	N/A	55.9 (22.0)	75.9 (29.9)
Leg length	Crotch height	249	66.5 (26.2)	95.8 (37.7)
Knee break	Knee height mid-patella	873	39.6 (15.6)	57.9 (22.8)
Torso sizing	Chest breadth	223	23.6 (9.3)	39.4 (15.5)
Torso sizing	Chest depth	236	19.1 (7.5)	30.2 (11.9)
Neck ring and helmet sizing	Head length	441	17.3 (6.8)	21.6 (8.5)
Maximum circumference of upper leg	Thigh circumference	852	47.8 (18.8)	71.9 (28.3)
Maximum circumference of upper arm	Biceps circumference flexed	111	22.9 (9.0)	40.4 (15.9)
Torso sizing	Chest circumference	230	75.7 (29.8)	118.6 (46.7)
Arm sizing	Inter-wrist distance	N/A	115.1 (45.3)	161.8 (63.7)
Functional arm break, arm length	Inter-elbow distance	N/A	72.6 (28.6)	101.3 (39.9)
Lower torso sizing	Waist depth	N/A	15.0 (5.9)	30.0 (11.8)
Lower torso sizing	Hip breadth	457*	29.7 (11.7)	40.6 (16.0)
Arm sizing	Wrist-to-wall distance	N/A	54.6 (21.5)	77.7 (30.6)

*For standing measurements, the largest female hip breadth is larger than the largest male hip breadth; therefore, female data are used for both the Min dimension and the Max dimension.